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Recovery of By-Products from Animal Wastes A Literature Review

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Recovery of By-Products from Animal Wastes

A Literature Review

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The primary purpose of this report was to identify and summarize by-product-from-animal-wastes-recovery processes from the current literature. By-product recovery processes are distinguishable from wastes reuse and recycle processes by the formation of a chemically or physically changed product or by-product from the wastes as produced.

Most of the schemes investigated were grouped into either biological or thermochemical processes. Methane production, a biological process utilizing anaerobic fermentation of the wastes, is receiving the greatest amount of popular and scientific attention. The economics of methane storage is the strongest deterrent to the development of this process for widespread application.

Thermochemical processes investigated include conversion to oil and oil-like tars; anhydrous ammonia synthesis gas and ethylene; hydrogasification; manufacture of carbon black, carbon black substitutes, and fillers and foaming agents in foam glass construction materials; and other fuels and construction products.

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RECOVERY OF BY-PRODUCTS FROM ANIMAL WASTES--

A LITERATURE REVIEW

by

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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate and management of pollutants in groundwater; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows, (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries, and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to the knowledge essential if the EPA is to meet the requirements of environmental laws that it establish and enforce pollution control standards which are reasonable, cost effective and provide adequate protection for the American people.

William C. Galegar

William C. Galegar, Director
Robert S. Kerr Environmental
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ABSTRACT

The primary purpose of this report was to identify and summarize by-product-from-animal-wastes-recovery processes from the current literature. By-product recovery processes are distinguishable from wastes reuse and recycle processes by the formation of a chemically or physically changed product or by-product from the wastes as produced.

Most of the schemes investigated were grouped into either biological or thermochemical processes. Methane production, a biological process utilizing anaerobic fermentation of the wastes, is receiving the greatest amount of popular and scientific attention. The economics of methane storage is the strongest deterent to the development of this process for widespread application. However, the process does have promise if located near a constant consumer of the gas or where it can be injected directly into a gas pipeline or distribution system.

Thermochemical processes investigated include conversion to oil and oil-like tars; anhydrous ammonia synthesis gas and ethylene; hydrogasification; manufacture of carbon black, carbon black substitutes, and fillers and foaming agents in foam glass construction materials; and other fuels and construction products. Of these, the most promising processes appear to be the conversion to ammonia synthesis gas and ethylene and the manufacture of glass foam foaming agents.

None of the processes investigated have been demonstrated and optimized for full scale commercial use. The costs of constructing and operating a demonstration plant for even the most promising processes are prohibitive for further involvement from the research segments of the universities and animal production industry. This report covers a period from January 1, 1977 to December 31, 1977 and was completed as of December 31, 1977.

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BRITISH TO METRIC UNIT CONVERSION

PRESSURE UNITS

1 pound per square foot (lb/ft^2) = 4.885 Kilograms per square meter (Kg/m^2)
1 pound per square inch (lb/in^2) = 70.308 grams per square centimeter (gr/cm^2)

ENERGY UNITS

1 British Thermal Unit (BTU) = 777.9 foot-pounds = 107.5 Kilogram-meters

LENGTH

1 inch (in.) = 2.54 centimeters (cm)

VOLUME

1 cubic foot (ft^3) = 0.028 cubic meters (m^3)

CAPACITY

1 gallon (gal.) = 3.785 liters (l)
1 barrel (bbl) = 42 gallons = 158.97 liters (l)

WEIGHT

1 pound (lb) = 0.454 Kilogram (Kg)
1 ton (tn) = 0.907 metric ton (t)

TEMPERATURE

Celsius (c) = 5/9 (F-32) where F in temperature is degrees Fahrenheit

SECTION 1

INTRODUCTION

The number of beef cattle marketed in the United States has increased from approximately 13 million head in 1960 to approximately 40 million head in 1975. This increase is due to increases in population coupled with a change in preference toward beef as a food item. The demand for more and better quality beef has resulted in a radical change in animal production methods. Prior to marketing, an increasing majority of animals for slaughter are being fed under confined conditions. This trend even though most evident with beef cattle has also been observed in the hog, dairy, poultry, turkey, and sheep production industry. Recent unfavorable trends in grain and slaughter market conditions have confronted the confinement animal feeders in the past two to three years. Many small confinement feeding facilities have given way to larger more economically stable feedlots. With the advent of the concentration of animals into feedlots the industry was faced with many new adversities. The greatest of these adversities has been the problem of disposing of the horrendous amount of manure generated by these animals.

Traditionally, these manure wastes have been disposed of by spreading and incorporating them into croplands where they served as a nutrient source to the crop and as a soil conditioner. However, the accumulation of manure on large feedlots is such that there is not sufficient land suitable for disposal within an economical hauling distance (Wadleigh, 1968). Thus, storage which virtually forms mountains of manure near large feedlots is becoming a common problem.

This problem is compounded each time that a rainfall of an amplitude sufficient to cause a runoff event comes in contact with feedlot or stored manure surface. This runoff has been shown to transport large amounts of highly organic, nutrient, and salt-rich pollutants. When feeding facilities are located, as many of the earlier feedlots were, near a stream or other body of surface water or such that runoff drains into surface waters, this pollutant load causes dissolved oxygen sags and accelerated eutrophication and/or salinity problems which in turn are responsible for fish kills, degradation of aquatic communities, algal blooms, and a general deterioration of water for many beneficial uses.

Agriculturally and environmentally oriented researchers from a variety of government agencies, educational institutions, and industrial corporations have directed their efforts toward developing processes for the utilization of the wastes through recycle and/or byproduct recovery. Many of these

processes are very imaginative and range from recycling these wastes as they are produced as a feed ingredient back through animals to chemically and physically transforming the wastes into building materials, synthetic gases, plastics, and fabrics.

This report will identify and evaluate the current state-of-the-art of those manure wastes utilization systems which can be classified as byproduct recovery processes. The classic definition of byproduct recovery refers to the production of a secondary product in addition to a principal product. Considering meat, eggs, or animal fiber as a principal product, then manure wastes is a byproduct.

Utilization of manure as a primary resource to either biologically or thermochemically recover secondary byproducts which can be used as an asset internally or marketed externally to offset the costs of pollution controls is the primary consideration of this report. Byproduct recovery, for the purposes of this report, fall into two categories as follows: (1) biological processes including methanization, and "worm dirt" (worm castings or worm compost) production and (2) thermochemical processes which produce various gases, chars, oils, building materials, fertilizers, soluble hydrocarbons, and heat energy sources.

SECTION 2

CONCLUSIONS

By-product-recovery-from-animal-wastes-processes were found to be extremely varied. These range from biological fermentation for the recovery of methane gas and a stabilized soil conditioner to thermochemical processes to produce gases, such as ethylene and synthesis gas; liquids, such as oil, tars, and fertilizers; and solids, such as lamp black substitutes, construction materials, and pet foods.

Many of these processes appear to be very promising both from an economic and a wastes utilization standpoint based on the results of paper, bench, and small pilot scale studies. However, none of the processes have been developed or optimized to the extent that they can be reduced to commercial practice. There has been considerable interest within the research community and animal production industry to initiate and support these bench and small pilot scale stages of these processes. These efforts are usually discontinued due to the great expense involved with further demonstration and optimization of the larger commercial scale designs.

Many of the processes require that large numbers of animal units be located within a prescribed area to provide the quantity of wastes required to support the economic breakpoint for the process. The number of such areas is limited by the propinquity of animal production facilities. The engineering design of many processes investigated could be altered or modified to include other highly organic wastes, thus, reducing the number of animals required by increasing the variety of acceptable feedstocks. This would in turn make the process more economically feasible for a greater number of areas and would relieve the problem of animal wastes disposal over a larger expanse of the nation.

Of the processes investigated, biological fermentation is receiving the greatest research effort on a national scale. The process is limited, however, by the economics of compressing methane gas. Methane generation may have application if constructed near the site where the methane can be used as produced or piped directly into a natural gas or methane gas distribution line.

Based on available economic evaluations the Texas Tech Synthesis-Ethylene gas process appears to be the process with the greatest economic viability. A large number of animals are required within a relatively small area to economically provide the feedstock for this process. However, designing the facility to accept other organic wastes could improve the outlook for the process by making it available in areas with fewer animals while at the same time recovering synthesis gas and ethylene from a variety of organic solid wastes.

SECTION 3

RECOMMENDATIONS

1. Continued support should be given to the initiation and development of new concepts in the area of by-product recovery from animal wastes.

2. Demonstration and optimization of the more promising processes such as recovery of ammonia synthesis gas, ethylene, oil, lamp black, and construction materials should be accelerated. These processes not only have potential animal waste reduction qualities but also have energy source and conservation implications.

3. Engineering designs for by-product recovery processes should include consideration for highly organic wastes other than animal production wastes. The inclusion of wastes such as municipal refuse, field crop residues, stover, cotton seed hulls, domestic sludges, etc., could provide a continuous source of feedstock which could effectively make many of the processes available in areas where concentration of animals are not ample to maintain an economical feedstock supply.

4. Government agencies with research and demonstration responsibilities in program areas dealing with animal waste management, energy, ecological effects and the environment, and other related fields should review and strongly encourage research and demonstration of by-product recovery processes by Government, private, and corporate entities.

5. Consideration should be given to the establishment of positive governmental incentives which would encourage the installation, demonstration, and optimization of large commercial scale by-product recovery processes by corporate interests.

6. The characterization and evaluation of gaseous, liquids and solid waste streams generated by the processes under development have not been reported in the literature. These wastes will ultimately be discharged to our environment either directly or through some disposal scheme. The characteristics of many of these wastes may render them more harmful to the ecological balances in receiving environments than the original wastes under consideration. All process development and evaluation studies should include consideration for the evaluation of the environmental acceptability of such waste streams.

SECTION 4

BIOLOGICAL PROCESSES

METHANE GENERATION

Methane, which constitutes over 95% of the natural gas which supplies about one-third of the total current energy consumption of the United States, is a gaseous product of natural microbial anaerobic fermentation of organic matter (Anon., 1974a). This process may be observed in nature as the bubbling of "swamp gas" from swamps or lakes and streams receiving highly organic pollutants. Bio-gas is produced naturally and uncontrolled under anaerobic conditions typical of septic tanks, anaerobic lagoons, organic wastes storage tanks, and sewage treatment plants. In many cases, bio-gas has been collected and burned to supply the heat requirements of anaerobic digestion or used to fuel internal combustion engines that can generate up to two-thirds of the power requirements for modern sewage treatment plants (Sweeten, 1974). Sewage treatment facilities in Chicago and Los Angeles are typical examples for such use of bio-gas generated by their anaerobic digestion process (Anon., 1974a). Bio-gas is produced naturally as a gas in swine buildings with slotted floors over pits (Day, Hansen, and Anderson, 1965).

Historical Background

The formation of methane gas from natural anaerobic digestion was discovered in 1776, but it was not characterized until 1806 (Goeppner and Hasselmann, 1974). In 1886, the fact that methane was formed by the biochemical actions of microbial cultures (anaerobic digestion) was confirmed (Geoppner and Hasselmann, 1974). A plant was installed in Bombay, India, in 1905, to produce both methane and the good fertilizer residue (Singh, 1973). During World War II, Germany built many plants for both methane and fertilizer due to the shortage of conventional fuels. The compressed gas was used to drive tractors and machinery (Anon., 1974a and Singh, 1973).

In the 1960's, Allred (1966) observed that methane utilization had ceased in Northern Europe. However, dwindling supplies of fossil fuels and increasing demands for the type of energy which they can produce has created a revived interest in methane production by anaerobic digestion of animal manure (Sweeten, 1974). Today thousands of bio-gas plants are in use in Algeria, South Africa, Korea, France, Hungary, and many other countries (Singh, 1973). A Redkey, Indiana, farmer has constructed a methane generator. The gas produced is used for fuel to operate a cook stove, refrigerator, gas light, small space heater, and a water heater plus a converted gasoline engine generated electric welder (Anon., 1974b).

Process Dynamics and Design Consideration

In his treatise on methane production from animal wastes, Smith (1973) presents a review of the literature pertinent to the chemical and biological fundamentals of methane production. In this presentation he combines the data reported by several researchers on such topics as: the presence and effect of toxic substances on process operation; gas production as a function of temperature and time; gas production and system performance; schematic diagrams of methane generators; performance parameters for the anaerobic digestion of livestock wastes by species; guidelines for maximum loading rates; and an example calculation of the amount of electrical energy that could be produced by a digestion-operated methane generator which in turn utilizes the wastes from a given number of animals. Several other investigators have described the basic principles of the process (Goeppner and Hasselmann, 1974; Schneider, 1972; Fry, 1973; Loehr, 1974; Meenaghan et al., 1970; and Savery and Cruzan, 1972). Figure 1 is a materials flow-through diagram for anaerobic digesters (Anon., 1974a). Figure 2 is a schematic diagram of a typical bio-gas generator (Fairbank, 1974). Schematic diagrams were also depicted by Loehr (1974), Wolf (1974), and Goeppner and Hasselmann (1974). Singh (1973) offers an engineering design for a bio-gas generator, and Fry (1973) discusses the basic principles of methane digestion for fuel gas and fertilizer and gives instructions for two working models.

Gas Characteristics and Yields

Bio-gas is characteristically a mixture of methane, CO_2, and miscellaneous other gases. Bohn (1971) reports that microbial fermentation yields a gaseous mixture of up to 72% methane, 25% or more carbon dioxide, ammonia, and hydrogen, plus small amounts of other gases such as mercaptans and amines.

Bio-gas production is dependent upon the activity of microorganisms which reduce organic material in an anaerobic environment. Specific organisms have varying temperature requirements. The most efficient of these microorganisms are divided into two groups based on their optimal temperature requirements (Savery and Cruzan, 1972). The first are called mesophilic bacteria which work at medium temperatures with optimum growth at 29° C. The second are called thermophilic bacteria which work at elevated temperatures with optimum growth at 51° C.

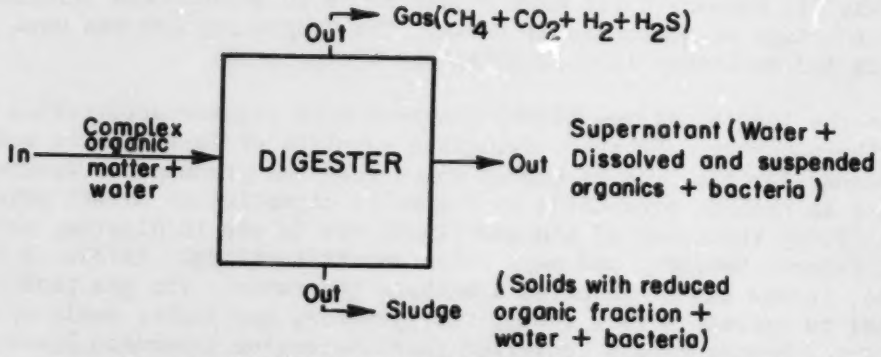


Figure 1. Overall material flow-through anaerobic digesters (Anon, 1974a).

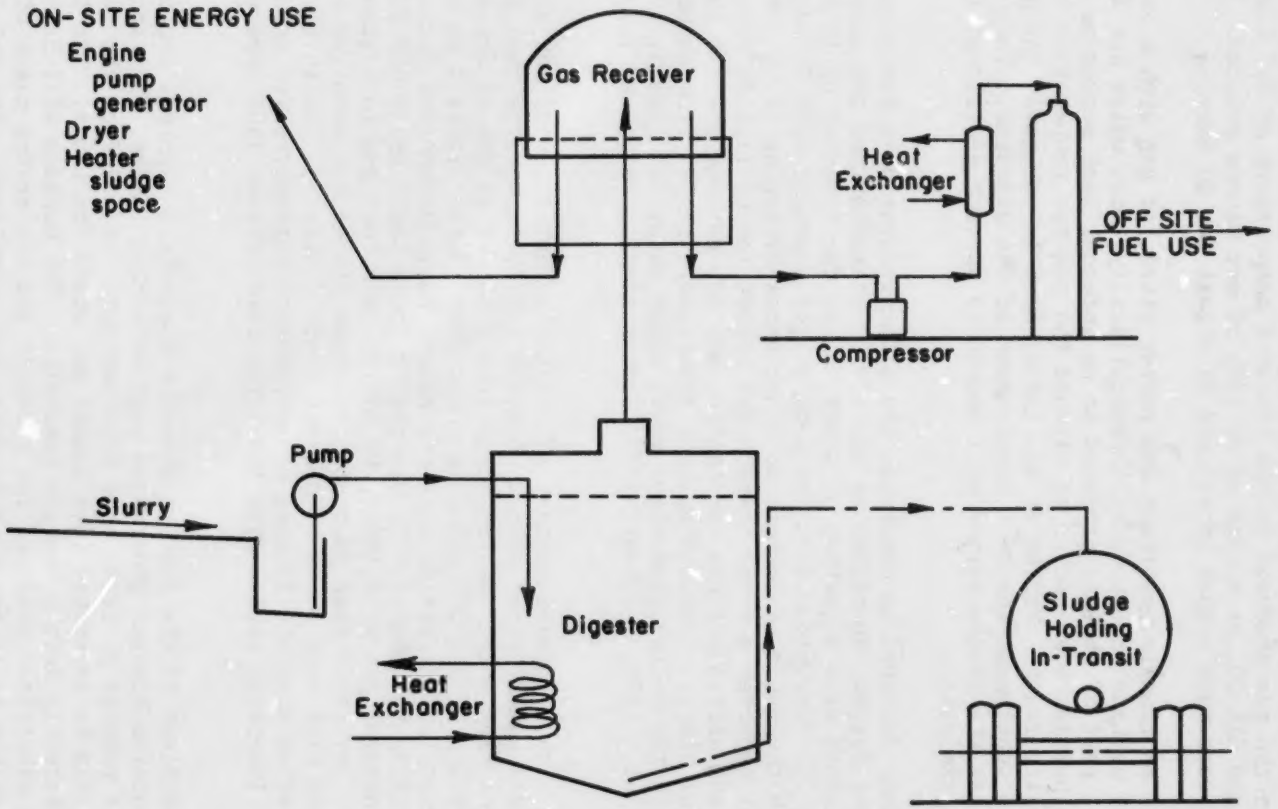


Figure 2. Components of bio-gas system (Fairbanks, 1974)

Savery and Cruzan (1972) report on the differences in gas characteristics produced by these two groups of bacteria from a single source of chicken manure digested for eight days. Gas produced by digestion in the 29° C range averaged 50% methane and 50% CO_2 at a rate of 46 l/kg of wet manure reacted. By comparison the gas produced at the elevated temperature of 51° C averaged 69% methane and 31% CO_2 at a rate of 89 l/kg of wet manure reacted. Mesophilic rates were much higher if allowed to digest for 20 days.

Inasmuch as time is important and better yields of gas with a larger percentage of methane are produced thermophilically, most units are designed to either use part of the gas produced as an internal heat source or to utilize some outside heat source to elevate the reactor temperature into the thermophilic range. Parker et al. (1974) have investigated the use of solar heat to supplement the heat requirement of the digester. They have determined that the system worked well enough to warrant additional investigation and optimization.

In a study designed to determine the effectiveness of a two-stage anaerobic treatment system, Meenaghan et al. (1970) characterized the gases and residues obtained from digestion of steer manure for a period of 10 days at 36° C (Table 1). Gas production for both stages averaged 3.56 ft^3/day/ft^3 capacity with the ratio of methane to other gases averaging 62.5%. Parker et al. (1974) reported a total maximum gas production of 11.5 ft^3/lb of volatile solids destroyed; gas composition was 60% methane and 40% CO_2. The composition of bio-gas produced by most researchers ranges from about 50% to about 75% with the median production level being about 60% (Smith, 1973; Meenaghan et al., 1970; Fairbank, 1974; Parker et al., 1974; and Taiganides, 1974).

Bio-gas with a methane content of 60% has a fuel value of 600 BTU/ft^3 (Fairbank, 1974 and Pfeffer, 1973). Sweeten (1974) summarizes that yields of methane gas from animal wastes range from 4 to 6.2 ft^3/lb of dry solids with a fuel value of 963 BTU/standard cubic foot (SCF). Table 2 is a comparison of expected gas yields on a per animal basis by species (Taiganides, 1974). According to Singh (1973) bio-gas in India tests about 650 BTU/ft^3 as compared to natural gas at 1,100-1,200 BTU/ft^3 and coal gas in England at 450 BTU/ft^3. For comparison purposes, Fairbank (1974) has compiled a listing of approximate high heat value of certain fuels (Table 3). Smith (1973) has compiled a rather complete listing of performance parameters for anaerobic digestion of livestock wastes from the literature between 1963 through 1971 (Table 4).

One consultant to the feedlot industry suggests a "systems approach" which incorporates bio-gas generation with refeeding (Andre, 1973 and Anon., 1974c). This process dictates that fresh excreta cleaned from the feedlot on a daily basis be separated into liquid and solid fractions. The liquid then is fed directly into a bio-gas generator. The methane will be used to generate the electrical needs of the feedmill and the drying needs of the dryer in which the solid fraction is dried and sterilized. The dried solids will then be incorporated with the feed for cows and calves and to a lesser

Table 1. A SUMMARY OF THE AVERAGE RESULTS OBTAINED FROM A COMPLETELY MIXED TWO STAGE DIGESTER WITH A CAPACITY OF 30 GALLONS PER STAGE, OPERATING AT 97° F AND A DAILY FEED RATE OF SIX GALLONS (Meenaghan et al., 1970)

Gas Production, ft^3/day/ft^3capacity, Stage 1, STP[a]	4.3
Stage 2, STP	2.82
CH_4,[b] %, Stage 1, STP	53
Stage 2, STP	72
C:N,[c] Feed	16.2
After 10 days digestion	9.4
pH, Feed	7.3
Stage 1	6.3
Stage 2	7.1
Volatile Acids, mg/l, Stage 1	2,990
Stage 2	1,030
Alkalinity, mg/l, Feed	2,100
Stage 1	3,750
Stage 2	4,700
Average BOD_5, mg/l, Feed	6,900
After 10 days digestion	2,900
Average COD, mg/l, Feed	13,000
After 10 days digestion	7,800

[a] STP - Standard Temperature and Pressure

[b] CH_4 - Methane

[c] C:N - Carbon-Nitrogen Ratio

Table 2. EXPECTED GAS YIELDS ON A PER ANIMAL BASIS (adapted from Taiganides, 1974)

Wastes	Gas Produced Cu ft/day	Methane Percent	Heat Value BTU/day
Swine	6.3	55-75	3,600
Cattle	42.0	60-80	25,000
Poultry	0.4	60-80	250

Table 3. APPROXIMATE HIGH[a] HEAT VALUE OF FUELS (adapted from Fairbank, 1974)

Fuel	Heat Value			Formula or Formulation Percent						
	BTU/lb	BTU/gal.	BTU/ft^3	CH_4	C_nH_m	CO	CO_2	H_2	N_2	O_2
Producer Gas[b]			157	2.5	.4	27	2.5	12	55	.3
Hydrogen			270					100		
Carbon Monoxide			316			100				
Water Gas[c]			322	2		45	4	45	2	.5
Pyrolysis Gas[d]										
Municipal			375	*	*	*	*	*	*	*
Feedlot			500	24	10	17	22	27	*	*
Bio-Gas[e]			620	60			35	*	*	
Coal Gas[f]			680	40	4	6	.5	46	1.5	.5
Methane	23,861		994	100						
Natural Gas			1,050	92.6	.3	.5		2.2	3.6	.3
Propane	21,591	91,547	2,516	C_3H_8						
Butane	21,221	102,032	3,280	C_4H_{10}						
Cattle Manure:										
Air Dry	5,000			$(C_{33}H_{48}O_{12})$ + 18% to 52% ash + moisture						
DM only	6,730			$(C_{33}H_{48}O_{12})$ + 18% to 52% ash						
VS only	9,100			$(C_{33}H_{48}O_{12})$						
Hardwood	7,100									
Softwood	9,000									
Coal	13,000									
Alcohol, Methyl	11,500	63,700	958	CH_4O						
Alcohol, Ethyl	16,700			C_2H_6O						
Dungoil	15,000									
Diesel, #1	19,600	135,250								
Kerosene	19,830	134,100								
Gasoline	20,300	124,100								
Fuel Oil, #2	20,150	133,000								

[a]High heat value includes the latent heat of condensation of resultant water vapor, which is not possible in farm operations or internal combustion engines.

[b]Hot coal + blast of air ($2C + N_2 + O_2 \rightarrow 2CO + N_2$)

[c]Hot coal + steam after heating w/air ($C + H_2O \rightarrow CO + H_2$)

[d]Farm Resource Science, Inc., Santa Ana, January 1974

[e]Also called manure methane or swamp gas; derived from the anaerobic decomposition of organic matter

[f]Destructive distillation of coal.

*Present in varying amounts.

Table 4. PERFORMANCE PARAMETERS FOR ANAEROBIC DIGESTION OF LIVESTOCK WASTES
Adapted from Smith, 1975

Manure	Loading		Temperature		Duration[a]	Dentention[b]	Mixing		VS Reduction	COD Reduction	COD Influent	$(NH_3 + NH_4^+)$-N	Volatile Acids	Alkalinity	Gas Production		Fraction as CH_4	pH	Source
	lb VS day / ft^3	lb V day / m^3	°F	°C	Day	Day	Natural	Intermittent Continuous	%	%	mg O_2/mg VS	mg/l	mg/l as HAc	mg/l as $CaCO_3$	ft^3 (lb VS) removed	m^3 (Kg VS) removed	%		
Dairy bull manure (from holding tank)	0.24	3.8	90.5	32.5	-	10		X	19.4	9.33	✓	45,200	206	216	3,320	6.33	0.4	65.2	6.93	A
"	0.24	3.8	90.6	43.6	-	15		X	17.7	13.2	-	68,270	376	177	5,160	8.88	0.56	61.5	7.09	A
Dairy cow urine and feces	0.202	3.1	74	23	37	26.3		X	10.4	-	1.00	-	1,240	<1,000	8,000	16.1	1.01	64	7.5	B
"	0.176	2.8	95	35	20	16.6	X		48.3	-	-	-	-	162	-	6.15	0.38	65	7.1	C
Beef manure (concrete floor)	0.1[c]	1.6	95	35	-	10		X	55.2	23.8	-	-	-	100	1,500	13.7[c,d]	0.86[c,d]	58	6.7	D
"	0.2[c]	3.2	95	35	-	10		X	41.9	28.6	-	-	-	100	2,050	17.7	1.11[c,d]	57	6.8	D
Hog Urine	0.075	1.2	93	34	110	22		X	47	-	1.32	-	1,300	1,500	6,800	19.6	1.23	59	7.4	E
"	0.025	0.4	93	34	40	48		X	43	-	1.32	-	1,200	1,200	6,800	23.5	1.47	50	7.4	E
Hog manure scraped from solid floor	0.12	1.9	90.5	32.5	-	15		X	60.9	54.6	-	35,000	584	200	4,440	11.1	0.69	60	7.14	A
"	0.24	3.8	90.5	32.5	-	10		X	44.2	35.5	-	46,000	750	1,080	6,330	13.2	0.83	58	7.17	A
"	0.24	3.8	90.5	32.5	-	15		X	59.2	41.8	-	70,000	1,010	290	7,150	12.2	0.76	59	7.27	A
Sheep urine and feces	0.150	2.4	95	35	13	20	X		38.0	-	-	-	-	95	-	9.7	0.61	65.5	7.3	C
Fresh poultry manure	0.12	1.9	90.5	32.5	-	10		X	67.2	75.3	-	40,580	1,020	350	-	7.28	0.45	58.0	7.2	A
"	0.12	1.9	90.5	32.5	-	15		X	67.8	78.1	-	60,920	1,570	175	-	8.56	0.53	57.8	7.35	A

A Gramms et al. (1971)

B Hart (1963)

C Jeffrey et al. (1964)

D Loehr & Agnew (1967)

E Taiganides (1963)

[a]Length of run at steady loading rate.

[b]Detention time calculated from:

$$\frac{\text{Total volume (or weight) of digester contents}}{\text{Volume (or weight) added daily}}$$

[c]Expressed on the basis of total not volatile solids

[d]Calculations made by the author, using the original data.

degree fed back to the feeder animals. The digested liquid exhausted from the generator is estimated to contain 2% to 3.5% of the solid fraction or about 2,880 lbs of nitrogen daily for a 10,000 head unit.

As indicated in the above systems approach, there is a useable residual product of the methane generation process. According to Sweeten (1974) this residue is a "well-composed manure" amounting to one-third the raw manure input. Another source (Anon., 1974a) indicates that the remaining sludges from the process constitute approximately 50% of the volume of the solid feed material. By comparison composted chicken manure has from 1.58% to 2% nitrogen while the same manure digested in a bio-gas plant will analyze 6% nitrogen (Singh, 1973). Thus, the residual sludge should have fertilizer and soil conditioning qualities when applied to crop land; however, there was not any indication as to the amount of residual salt levels in these sludges.

Economics

Until recently, the cost of methane production by recovering bio-gas from controlled anaerobic digestion processes has been very prohibitive. In 1972, for example, Costigane (1972) concluded, after making an intensive investigation into the theory and feasibility of anaerobic digestion, that the most economical and efficient design presently available for methane production and wastes stabilization "is not at present considered feasible for animal waste treatment on a small farm due to the high initial equipment costs." Tests conducted by Savery and Cruzan (1972) on an experimental digester for the production of methane gas from chicken manure indicated that a 60,000 chicken unit could supply sufficient quantities of methane to be self-sufficient in its total electricity requirements. However, the costs were six times that of its present supply. Smith (1973) concludes that anaerobic digestion is only a partial stabilization process which must be followed by additional, potentially expensive process; that increased handling costs are due to increased volumes which are created by solids dilution; and that costly management and supporting services are required to run an anaerobic digester.

However, when considering the world energy situation and related needs for renewable energy sources, bio-gasification of organic wastes is an important possibility for consideration. Some preliminary estimates have been made in consideration of this need. Fry (1973) reports that people with the United States standard of living use 60 ft^3/day/person of natural gas (60,000 BTU). He further estimates that under optimal conditions, 10 pounds of wastes would generate this amount of methane based on the production of 10 ft^3/lb of volatile solids destroyed. And according to estimates of Solomon (1972), if all of the nation's animal wastes were anaerobically digested, 10^{13} ft^3 of methane fuel could be produced annually. This is nearly half of the current United States methane consumption. A more conservative estimate of from 10 to 20 percent of the current United States natural gas consumption could be replaced by the anaerobic digestion of all agricultural organic wastes (both wastes from crop production and animal wastes) which could be economically collected was made by Wolf (1974).

On process costs, Pfeffer (1973) estimates that the operating costs for a digester ranges from $4.35 to $3.54 per million BTU of gas generated. Whereas, Boln (1971) presents a "conservative rule of thumb;" one ton of dry organic matter produces 20,000 ft^3 of methane worth about $3.40 at the 1971 well-head price of 17¢ per thousand cu ft.

Methane cannot be liquified under normal temperatures (Lapp et. al 1975) (Hansen 1976). This characteristic makes storage uneconimical due to the large storage capacities required to store it in the gaseous form. Barth and Hill (1975) suggest that the CO_2 which occupies one-third of the gas volume be scrubbed by passing the gas through adilute albaline solution. The nearby pure methane can then be utilized at approximately the same rate at which it is produced. According to Hansen (1976) bio-gas should be used for such low demand stationary uses as cooking, heating water and buildings, air conditioning or stationary engines. The high compression required to store enough bio-gas on a tractor for one hours operations creats a serious safety hazzard.

EARTHWORM CASTINGS

Worm dirt (earthworm castings or feces) is the material which passes through the gut of earthworms. The earthworm is very efficient at neutralizing or composting highly organic wastes. Fosgate and Babb (1972) intensively cultivated earthworms on a media of cow manure. Worms require a media with 9%-15% protein content. The manure used contained about 14.25% protein and required the addition of lime to maintain a neutral 7.0 pH. A raw feces to live earthworm conversion ratio of 10:1 was obtained. The average mineral composition of the cattle feces, earthworms, and earthworm feces on a dry matter basis is presented in Table 5.

The earthworms, dried into a meal, were found to be very palatable to cats. The earthworm dirt is a very good soil conditioner which only weighs about 50% as much as normal potting soil.

Another investigator (Hancock, 1956) reported on the raising of worms on a ration of peat moss, commercial laying mash, corn meal, and a small amount of molasses. The compost produced by their excrement was harvested and fed to broilers which grew to 3.5 lbs in weight in 8 weeks. The other half of the same flock, raised on regular commercial broiler feed, required 10 weeks to reach three lbs.

There have not been any studies of the use of "earthworm compost" as a refeeding mechanism to animals other than broilers or of pollutional characteristics of the process reported in the literature.

Table 5. AVERAGE MINERAL COMPOSITION OF CATTLE FECES, EARTHWORMS, AND EARTHWORM CASTINGS (DM BASIS) (Fosgate and Babb, 1972)

Source	N	P	K	Ca	Mg
Cow Feces	2.36	0.72	0.73	1.43	0.55
Earthworm	9.31	0.90	0.88	0.54	0.19
Earthworm Castings	2.98	0.32	0.40	1.20	0.36

SECTION 5

THERMOCHEMICAL PROCESSES

Highly organic materials such as animal manure and other solid wastes can be changed chemically by subjecting them to highly elevated temperatures. The chemical transformation can be selectively controlled through regulation of the atmospheric content and pressure. Such controlled heat induced chemical changes are a result of thermochemical processing. Providing that favorable economics exist, Whetstone (1973) reports thermochemical processing of manure as the most acceptable alternative to land spreading.

Cow and/or buffalo chips provided the primary source of fuel to pioneer settlers of the high plains of West Texas. These chips were burned to heat houses and provide cooking heat. Wells et al. (1973) observed that feedlot manure used directly as a fuel does not appear promising. His observation was based on a preliminary experiment in which he rolled feedlot manure into dried logs, "Blue Flame Buffalo Chips," which did not readily burn with a flame but which smoldered to an ash giving off very little heat.

Incineration of animal wastes for the sole purpose of disposal is practiced on a very small scale. Davis et al. (1972) reported a manure weight reduction of about 90% and a volume reduction of about 85% by incineration. The economics of this process are not attractive because there is not any economic return for the equipment, investment, maintenance, or operation costs other than the intrinsic value of manure disposal. The processes discussed herein utilize combustion of manure in one form or another and have as a common demoninator the potential for recovery of a useable or saleable product which will provide some economic return to the feeding operation.

PYROLYSIS

Pyrolysis, a common chemical process, is thermal decomposition that can be achieved by heating organic materials in an inert atmosphere or by partial combustion (Garner and Smith, 1973). The process equipment must include a heat source, a pyrolysis or reaction chamber, and a system to separate product gases, condensates, tars, chars, and ash. The process equipment may either be designed to handle the feedstock on a batch basis or with a continuous flow of feedstock. Pyrolysis has been used for several hundred years to make charcoal and in more recent times to recover by-products such as methanol, acetic acid, and turpentine (Loehr, 1974).

White and Taiganides (1971) reported that product yields for batches of swine, beef, dairy, and poultry manure were similar. Garner and Smith (1973) pyrolyzed steer manure containing 80% moisture. They identified many oxygenated and nitrogenous organic compounds, none of which were produced in quantities which were sufficient to economically justify separation. They reported that the costs of pyrolysis for the disposal of manure was approximately $5.60 per ton and thus, not economically attractive.

Schlesinger et al (1972) reported the data presented in Table 6 for manure pyrolyzed in a batch reactor designed for the testing of coal.

The value of the liquid pyrolysate from this process was placed at no more than the current price of crude petroleum and coke oven tars. When compared to simple incineration, Garner et al. (1972) concluded that their pyrolysis process was uneconomical due to equipment and separation costs. The costs of pre-drying was most uneconomical and accounted for the largest liability to the project. The manure used was as produced or about 80% moisture. Their economics did not consider dryer manure as cleaned from lots in more arid regions of the country.

Whetstone (1973) warns that the yields for pyrolysis of manure are a complex function of many variables. These variables include manure composition and particle size, heating rates, maximum temperature, and pressure in the pyrolysis chamber. For particular pyrolysis schemes, other factors may also influence the product yields; among these are the purging of the reactor chamber with gases or the allowing of liquid products to reflux back into the pyrolysis chamber. For these reasons considerable judgement must be exercised in drawing conclusions from published data for batch pyrolysis of manure.

Continuous pyrolysis of manure is complicated by requirement of maintaining stable, constant reactor heat and pressures while continuously feeding manure through the reactor and at the same time recovering the products of pyrolysis. Several methods have been developed to continuously pyrolyze such feedstocks as municipal solid wastes, non-compostable wastes, oil shale, coal, and other organic materials. While most of these processes could have applicability for animal wastes, there has only been one continuous manure pyrolyzer reported in detail. This pyrolyzer or retort as it is called employs air injection to energize pyrolysis reactions in a moving bed (Massie and Parker, 1973). This retort is detailed in Figure 3. The feedstock enters the top of the retort and the product char and ash is discharged through the bottom. Counterflow circulation of gases serve to transport heat upward in the retort to form manure drying and pyrolysis zones in the upper section of the retort. Two gas injection cycles are employed. Air is injected to generate heat at a combustion front which moves downward in the retort when the lower portion of the retort is cold. The injected air is diluted with oxygen-free gas to lower the temperatures at the combustion front, so that the ash in the manure cannot fuse and form clinkers. When the combustion front nears the bottom of the retort where the associated high temperatures might damage the grate, air injection is stopped and only oxygen-free gas is injected. The oxygen-free gas cools the lower portion of the retort and continues the pyrolysis and drying of manure in the upper portion of the retort. When the lower half of the retort has cooled, air injection is again resumed.

Table 6. CHARACTERISTICS OF RAW PRODUCTS FROM THE PYROLYSIS OF MANURE

	Batch Pyrolysis			Continuous Pyrolysis	Oil Production	Hydrogasi-fication		Ammonia Synthesis Gas		Cyclonic Burner	TCD-Char
	A	B	C	D	E & F	G	H	I	J	K	L
Ultimate Analysis of Feed, Wt.%											
Carbon	41.2	*	*	*	20.5	35.4	35.4	35.1-39.6	42.6	27.6	23.82
Hydrogen	5.7	*	*	*	2.5	4.2	4.6	5.3-5.9	5.5	3.76	3.80
Oxygen	33.3	*	*	*	14.5	23.5	30.1	0.0	23.7	21.48	*
Nitrogen	2.2	*	*	*	1.3	0.7	*	2.5-3.1	2.8	2.32	1.85
Sulfur	0.3	*	*	*	0.5	0.2	*	0.4-0.6	0.5	0.5	*
Ash	17.2	8.65	*	22.0	15.1	36.0	25.6	23.5-29.2	24.9	44.30	*
Yields (per ton of wet feed)											
Gas (Std. cubic feet)	13,940	104.4[a]	381[b]	16,610	*	.967[c]	*	8,400-15,000[d]	790[a]	16,208	*
Oil (bbl)	0.31	0.25	*	0.96	2.6	0.0	*	0.88[e]	0.14	1.0[e]	*
Waterphase (gal.)	38.3	222	*	89.5	*	.872[c]	*		42		*
Char (lb)	726	143	0.33[f]	526	*	40.6[g]	*	93	650	1,093	*
Oil Composition, Vol. %											
Carbon	*	*	*	*	78.6	*	*	*	*	*	*
Hydrogen	*	*	*	*	9.5	*	*	*	*	*	*
Nitrogen	*	*	*	*	4.2	*	*	*	*	*	*
Sulfur	*	*	*	*	0.37	*	*	*	*	*	*
Oxygen	*	*	*	*	7.3	*	*	*	*	*	*
Gas Composition, Vol. %											
Oxygen	0.0	0.0	4	1.72	*	0.0	0.0	0.3-2.5	0.0	3.5	*
Nitrogen	0.0	7	19	49.83	*	0.0	0.0	28.4-33.3	7.1	65.8	*
Carbon dioxide	24.5	37.2	18	14.06	*	33.5	16.11	13.1-18.7	14.2	22.5	*
Carbon monoxide	18.0	16.7	18	17.72	*	0.7	3.4	11.5-17.3	12.8	4.8	*
Hydrogen	27.5	16.4	30	10.2	*	11.3	10.56	18.1-26.2	27.4	2.2	*
Methane	22.7	15.5		3.07	*	42.1	18.55	6.2-7.9	32.3	0.6	*
Ethylene	0.0	0.4	13[h]	*	*	0.0	0.0	2.7-4.1	5.9	0.6	*
Ethane	0.0	1.7		*	*	12.4	5.38	<=0.3	0.4	*	*
Carbon	7.3	*	0.0	*	*	0.0	0.0	0.0	0.0	*	*
Water	0.0	*	0.0	*	*	0.0	45.85	0.0	0.0	*	*
Hydrogen Sulfide	0.0	*	0.0	*	*	0.0	0.15	0.0	0.0	*	*
Char, Wt. %											
Carbon	49.4	*	63	*	*	*	44.1	32.0-41.2	*	21.54	30.07
Hydrogen	0.4	*	*	*	*	*	1.6	0.3-1.6	*	1.07	1.49
Oxygen	0.4	*	*	*	*	*	0.0	*	*	*	*
Nitrogen	1.1	*	*	*	*	*	0.0	2.0-2.5	*	1.42	0.0
Sulfur	0.3	*	*	*	*	*	0.0	*	*	*	*
Ash	48.4	*	36	40	*	*	54.2	36.7-53.9	21.5	76.40	*
Heating Values											
Feed, BTU/lb. (dry)	7,110	*	*	7,630	*	*	*	3,194-3,739[i]	6,350	5,604	*
Gas, BTU/ft^3	450	4,200	1,900[j]	123	*	1,000+	*	*	*	*	*
Char, BTU/lb. (dry)	7,290	11,000	3,000	6,390	*	*	*	4,132-5,535[i]	*	2,011	*

A - Schlesinger et al. (1972)
B - Garner and Smith (1973)
C - White and Taiganides (1971)
D - Massie and Parker (1973)
E - Appell and Miller (1972)
F - Appell et al. (1971)
G - Kiang et al. (1973)
H - Feldman et al. (1973)
I - Halligan et al. (1974)
J - Huffman and Halligan (1974-75)
K - Natour et al. (1975)
L - Mackenzie (1976)

* Not reported
a - lbs/T of wet feed
b - mg/l
c - moles/80 gr.
d - H_2 + CO
e - bbl/ton of feed, oil plus waterphase
f - gr./gr. of total solids
g - gr./80 gr. feed
h - total combustibles and illuminants
i - Kg ccl/Kg
j - per lb of total solids

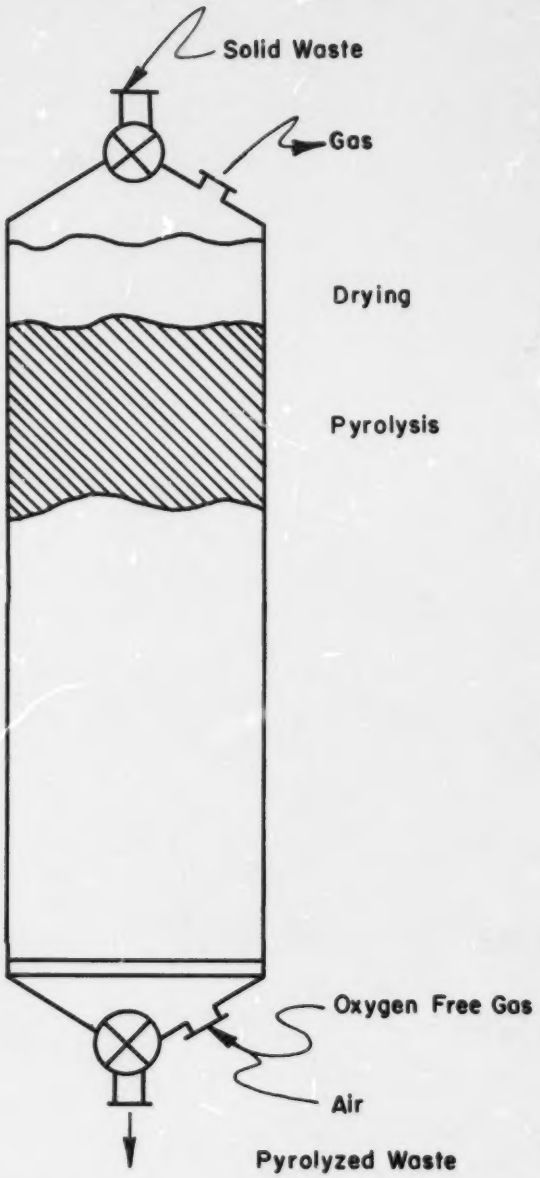


Figure 3. Continuous retort schematic (adapted from Massie and Parker, 1973)

Feasibility of this retort has been demonstrated in a six-inch pilot model. Table 6 reports the yield of products from this retort. A major difference in the list of observed pyrolysis products from the continuous retort and that reported for batch pyrolysis of manure is the yield of liquid organics. The continuous retort yielded about one barrel of oil per ton of manure processed in contrast with the 0.3 barrel per ton reported for the batch pyrolysis. These data show that manure pyrolyzed in the continuous retort produces more oil per ton of manure than is reported for average Colorado oil shale (20-30 gallons of oil per ton of oil shale). The increase in oil yield over that of batch pyrolysis is due to the rapid removal of pyrolysis products from the retort by the circulated gases.

Conceptual process flow sheets have been prepared for a commercial plant using the Texas Tech University retort and costs estimated by Parker et al. (1973). For a plant processing 2,000 tons per day of 30 percent moisture manure an investment of 14.7 million dollars has been estimated. When credit is taken for electric power generated and ammonium sulfate produced by this plant, the annual income exceeds the operating expenses, including maintenance, by $846,000 if the manure entering the plant be considered to have zero value. If no credit is taken for oil and char produced, the cost of manure processing is several dollars per ton with a 14 percent rate of return for industrial economics and $1.70 per ton for municipal economics using the criteria from Table 7.

Table 7. ECONOMIC CRITERIA FOR EVALUATION OF PROCESS COSTS
(Adapted from Parker et al., 1973)

	Public Ownership Economics	Private Ownership Economics
Size (tons/day)	2,000	2,000
Project Life (yr)	20	20
Depreciation Schedule	20 yr straight line	11 yr sum of digits
Interest Rate (year end discount)	6%	14%
Income Tax	0.0	48%
Fixed Capital Investment, FCI	4.1 of major equipment costs	
Maintenance	4% of FCI/yr	
Salvage	5% of FCI	
Supervision	20% of labor	
Payroll	25%	
Plant Overhead	50% of labor	
Working Capital	5% of FCI	
Insurance and Local Taxes	2% of FCI	

The preceding pyrolysis methods, with energizing by partial combustion of the solids being pyrolyzed, result in pyrolysis gases which are diluted with nitrogen and combustion gases. For a price, dilution with nitrogen can be avoided by using oxygen instead of air to oxidize the fuel as has been proposed for several coal pyrolysis and gasification methods. Cyclic operation of the pyrolysis processes can also be utilized to produce pyrolysis gases not contaminated with nitrogen or combustion gases.

Other thermochemical processes to convert manure into selected gases, liquid and solid fractions have been developed by controlling various conditions of pyrolysis. For example the amount of carbon in the char can be controlled by varying the pyrolysis reactor temperatures. A detailed description of liquification to oil, gasification of synthesis gas, and hydrogasification to methane manure processing schemes have been presented by Walawender et al. (1973a). A detailed economic analysis of these processes has also been presented by Walawender et al. (1973b).

OIL PRODUCTION

The U.S. Bureau of Mines has developed a means to convert organic wastes to low sulfur fuel by exposing them to CO and Na_2CO_3 as a catalyst at high pressures and temperatures. Urban refuse and cellulosic wastes pyrolyzed at temperatures between 250° and 400° C and at pressures of from 1,500 to 5,000 psi will yield about two barrels of low sulfur (0.1%) oil per ton of ash-free feedstock. This conversion of organic matter to oil, water, and gas is about 90% efficient with the yield of oil usually near 40% (Appell et al., 1970). Animal wastes conversions are essentially complete at 380° C in the absence of solvents, but pressures of 5,000 to 6,000 psig are obtained because of combined high steam and gas pressures generated with wet manures (Appell and Miller, 1972). Bovine manure, which is not readily converted to oil at 250° C as are other organic wastes, will produce highest conversion efficiencies at 380° C and high temperatures after pre-treatment with CO and steam. Catalysts are not needed due to characteristically high calcium, sodium, and potassium content of animal wastes (Appell et al., 1971). The composition of cattle manure feedstock and the oil product is shown on Table 6. The composition of product oil from cattle and chicken manure is shown in Table 8.

Walawender et al. (1973b) presented an economic evaluation of the manure to oil process based on 1973 cost considerations. This evaluation was based on a plant with a capacity to handle 4,300 tons of wet manure feedstock per day. The analysis also considers that the process will produce one barrel of oil per ton of wet manure rather than the two barrels estimated by Appell et al. (1970). These estimates show a capital investment of $44,180,200 (Table 9) and a total product cost per pound of $0.0326 (Table 10). These capital investment costs and total product costs have increased in the period from 1973 to 1975; however, crude oil in the same period has increased from $0.02 per pound to $0.037 per pound. Process economics, even with the increase in crude oil prices, remain unattractive when attempting to encourage further development and optimization of the process by the private sector.

Table 8. COMPOSITION OF OIL FROM MANURE (Appell et al., 1971)

Manure	Temp. (° C)	Reactor Time (hrs.)	Analysis (%)				
			C	H	M	S	O[a]
Bovine	380	0.3	78.9	9.5	4.2	0.37	7.3
Bovine (PE)[b]	350	1	79.7	9.5	3.2	0.56	7.1
Chicken	350	1	75.4	9.7	6.8	0.26	7.8

[a]By difference

[b]PE = Protein extracted

Table 9. ESTIMATED CAPITAL INVESTMENT FOR OIL PROCESS (Walawender et al., 1973b)

Item	Cost
A. Direct Costs	
1. Purchase Equipment (delivered)	$ 8,955,200
2. Equipment Installation	4,029,800
3. Instrumentation and Controls (installed)	1,791,000
4. Piping (installed)	3,134,300
5. Electrical (installed)	1,074,600
6. Buildings	1,791,000
7. Yard Improvements	716,400
8. Service Facilities (installed)	4,925,400
9. Land	537,300
TOTAL DIRECT PLANT COSTS	$26,955,000
B. Indirect Costs	
1. Engineering and Supervision	$ 2,955,200
2. Construction Expenses	3,582,100
3. Contractor's Fee	1,791,000
4. Contingency	3,134,300
FIXED CAPITAL INVESTMENT	$38,417,600
C. Working Capital	5,762,600
TOTAL CAPITAL INVESTMENT	$44,180,200

Table 10. TOTAL PRODUCT COST ESTIMATE FOR OIL PROCESS
(Walawender et al., 1973b)

Item	Cost
I. Manufacturing Cost	$
A. Direct Production Costs	
1. Raw Materials	
Manure	1,413,200
Carbon Monoxide	4,842,000
2. Operating Labor	197,100
3. Direct Supervisory and clerical labor	29,600
4. Utilities	1,563,800
5. Maintenance and repairs	1,536,700
6. Operating supplies	192,100
7. Laboratory charges	19,700
B. Fixed Charges	
1. Depreciation	3,841,800
2. Local Taxes	384,200
3. Insurance	384,200
C. Plant Overhead Costs	98,600
II. General Expenses	
A. Administrative Costs	264,500
B. Distribution and Selling Costs	312,800
C. Research and Development Costs	469,100
D. Financing	88,400
ANNUAL TOTAL PRODUCTION COSTS*	$15,637,800
TOTAL PRODUCTION COSTS PER POUND*	$0.0326

* Basis: 4,282.5 tons/day wet manure feed, 330-day/year plant operation.

GASIFICATION

By reacting cattle manure with hydrogen at gasification (Hydrane process, Feldman et al., 1972) conditions, Kiang et al. (1973) showed that a suitable synthetic natural gas (SNG) could be produced. The conditions of this process called hydrogasification are shown in Table 11.

Table 11. SUMMARY OF REACTOR RESULTS FOR THE DIRECT HYDROGASIFICATION OF CATTLE MANURE (adapted from Kiang et al., 1973)

Reactor Tempterature, °C	550
Initial press, psig*	150
Operating press, psig*	1,630
Solid charge, grams	80
Hydrogen charge, g-moles	0.562
Solid residue, grams	40.6
Carbon in charge, g-moles	2.363
Gas produced, g-moles	0.967
Carbon gasified, %	40.4
Water recovered, g-moles	0.872

* psig = pounds per square inch gauge

These data show that cattle manure is readily converted to pipeline gas by hydrogasification at temperatures low enough to allow appreciable yields of ethane. Synthetic Natural Gas with a heating value in excess of 1,000 BTU/scf can be produced without any need for methanation by hydrogasifying the manure, shifting a low concentration CO to CO_2, and scrubbing out the CO_2. In addition, it was found that no tars or oils were produced from manure hydrogasification in spite of the relatively low temperatures. An experiment made by these researchers with cattle manure in a continuous free-fall dilute-phase reactor indicated that the manure in such a reactor system is more reactive than in the batch reactor because of the much higher rates and the low concentration of particles in the dilute phase reactor. An analysis of the manure feedstock and products from hydrogasification are presented in Table 6.

Walawender et al. (1973b) have presented some basic economic analysis of the hydrogasification process, Tables 12 and 13. The breakeven or total product cost of $2.02 per MSCF ($1 \times 10^6$ standard cubic feet) for the methane is about four times greater than the sale price of methane at the time of release of the above analysis. Thus the processing costs of the manure was $9.41 per ton as produced.

Feldman et al. (1973) estimated North Slope gas at $\$1.00/10^6$ BTU in 1973, and reported U.S. natural gas consumption at 24×10^{12} scf per year. The results of their study to convert cattle manure to pipeline gas by direct hydrogasification by the Hydrane Process (described in detail by Feldman et al. (1972) showed that supplying cattle manure containing 52% moisture to an

Table 12. ESTIMATED CAPITAL INVESTMENT FOR HYDROGASIFICATION PROCESS (Walawender et al., 1973b)

Item	Cost
I. Gasification System	$
A. Direct Costs	
1. Purchased Equipment (delivered)	1,269,500
2. Equipment Installation	571,300
3. Instrumentation and Controls (installed)	253,900
4. Piping (installed)	444,300
5. Electrical (installed)	152,300
6. Buildings	253,900
7. Yard Improvements	101,600
8. Service Facilities (installed)	698,200
9. Land	76,200
TOTAL DIRECT PLANT COST (Gasification System)	3,821,200
B. Indirect Costs	
1. Engineering and supervision	418,900
2. Construction Expenses	507,800
3. Contractor's Fee	253,900
4. Contingency	444,300
FIXED CAPITAL INVESTMENT (Gasification System)	5,446,100
FIXED CAPITAL INVESTMENT (Separation System)	1,500,000
FIXED CAPITAL INVESTMENT (Entire Process)	6,946,100
C. Working Capital	1,041,900
TOTAL CAPITAL INVESTMENT	$7,988,000

integrated pipeline gas plant yielded approximately 4.6 scf/lb of dry organic solids of 1,000 BTU/scf gas or at 159 mm ton manure/yr about 1.46 trillion scf/yr. This is about 5.8% of the total U.S. consumption or 24% of the U.S. residential and commercial gas consumption. The Hydrane Process was originally developed by Bureau of Mines for transforming unpretreated coal to pipeline gas.

Economic estimates for hydrogasification of 8,280 tons of wet manure/day (690,000 lb/hr manure feed rate)are presented in Tables 14 and 15.

Table 13. TOTAL PRODUCT COST ESTIMATE FOR HYDROGASIFICATION PROCESS
(Walawender et al., 1973b)

Item	Cost
I. Manufacturing Cost	$
A. Direct Production Costs	
1. Raw Materials	
Manure	330,000
Hydrogen	1,557,100
2. Operating Labor	157,700
3. Direct supervisory and electrical labor	23,700
4. Utilities	412,800
5. Maintenance and repairs	347,300
6. Operating supplies	69,500
7. Laboratory charges	15,800
B. Fixed Charges	
1. Depreciation	694,600
2. Local Taxes	69,500
3. Insurance	69,500
C. Plant Overhead Costs	78,900
II. General Expenses	
A. Administrative Costs	79,300
B. Distribution and selling costs	82,600
C. Research and Development costs	123,800
D. Financing	16,000
ANNUAL TOTAL PRODUCT COST*	$4,128,100
TOTAL PRODUCT COST PER MSCF*	$2.02

*Basis: 1,000 tons/day wet manure feed, 330-day/year plant operation.

Table 14. CAPITAL INVESTMENT SUMMARY FOR MANURE-TO-PIPELINE GAS PLANT (adapted from Feldman et al., 1973)

Manure rate, lb/hr	690,000 (design base)
Dryer	3,040,000
Hydrogasifier	1,326,750
Gasifier	2,273,000
Shift Converter	249,000
Gas Purification	6,562,000
Methanation	280,000
Oxygen Plant	4,812,500
Offsite Facilities	3,272,350
Contractors Overhead plus profit	1,686,350
Interest during Construction	1,175,100
Total Working Capital	521,230
Total Capital Investment	$25,198,280

Table 15. OPERATING COSTS, REVENUE REQUIREMENTS, AND GAS PRICES FOR MANURE-TO-PIPELINE GAS PLANT (adapted from Feldman et al., 1973)

Manure Rate, lb/hr	690,000 (design base)
Manure Cost	0.0
Other Direct Materials	100,320
Direct Operating Labor	722,700
Maintenance	654,470
Supplies	98,170
Supervision	72,270
Payroll Overhead	79,500
General Overhead	773,800
Depreciation	1,233,850
Local Taxes and Insurance	740,310
Contingencies	89,510
By-product Credit	0.0
Operating Expenses	$4,564,900
20-yr avg price of gas, $/$10^6$ BTU	$0.41
20-yr avg price of gas, $/MSCF*	$4.10

* 1 scf = 1,000 BTU

The present economics of the hydrogasification of manure by the Hydrane Process have been summarized by Halligan and Sweazy (1972). Their conclusion was that even though 27 ft^3 of methane could be produced from the manure excreted from each animal daily, the very high capital and operating costs required for a plant to accomplish the conversion would not be economically feasible. These researchers, however, offer a process with a potential production of approximately 2.5 pounds of anhydrous ammonia from the excreta of each feedlot animal daily. Thus, an ammonia synthesis to anhydrous ammonia conversion plant located near a major Texas Panhandle feeding center could obtain sufficient quantities of manure in a 15-mile radius to supply a 1,000 ton per day ammonia plant with each day's gas production. This would nearly equal the 1972 West Texas ammonia fertilizer consumption (Anon., 1973).

This process, developed at Texas Tech University (Herzog, 1973; Herzog et al., 1973; and Halligan et al., 1974), utilizes a mixture of manure, air, steam, and small stream of carbon dioxide which is fed into a fluidized-bed reactor to produce ammonia synthesis gas. Figure 4 is a flow diagram of the partial oxidation of manure to produce synthesis gas. In the initial phase of the process development a 4.1-cm diameter fluidized bed reactor was utilized, Figure 5. The synthesis gas was compatible with existing ammonia plant technology and suitable for subsequent conversion to anhydrous ammonia. A product analysis is presented in Table 6.

The H_2:N_2 ratios in the product gas as collected from the reactor were all less than 1.5:1 which are below the optimum 3:1 desired for ammonia synthesis gas. However, thermally reforming the gas with steam would produce ultimate hydrogen from the reforming of the methane and ethylene. This reforming would also purify the gas of hydrocarbons. Synthesis gas ratios obtained before and after reforming are shown in Table 16.

The economics of recovering ammonia synthesis gas from manure were reported by Wideman et al., (1974). A summary of the installed costs for the major sections of the plant is given in Table 17. The reactor section of the plant comprises the largest portion (42%) of the investment. This is due largely to the size and number of reactors, as well as the need for

Table 16. SYNTHESIS GAS RATIOS OF THE PRODUCT GASES (Halligan et al., 1974)

Ultimate H_2:N_2	Run Number 1	2	3	4	5	6
Before reforming	1.5	1.0	1.0	1.1	1.4	1.1
After reforming - based on gas analysis	3.1	2.1	2.5	2.9	2.9	2.5

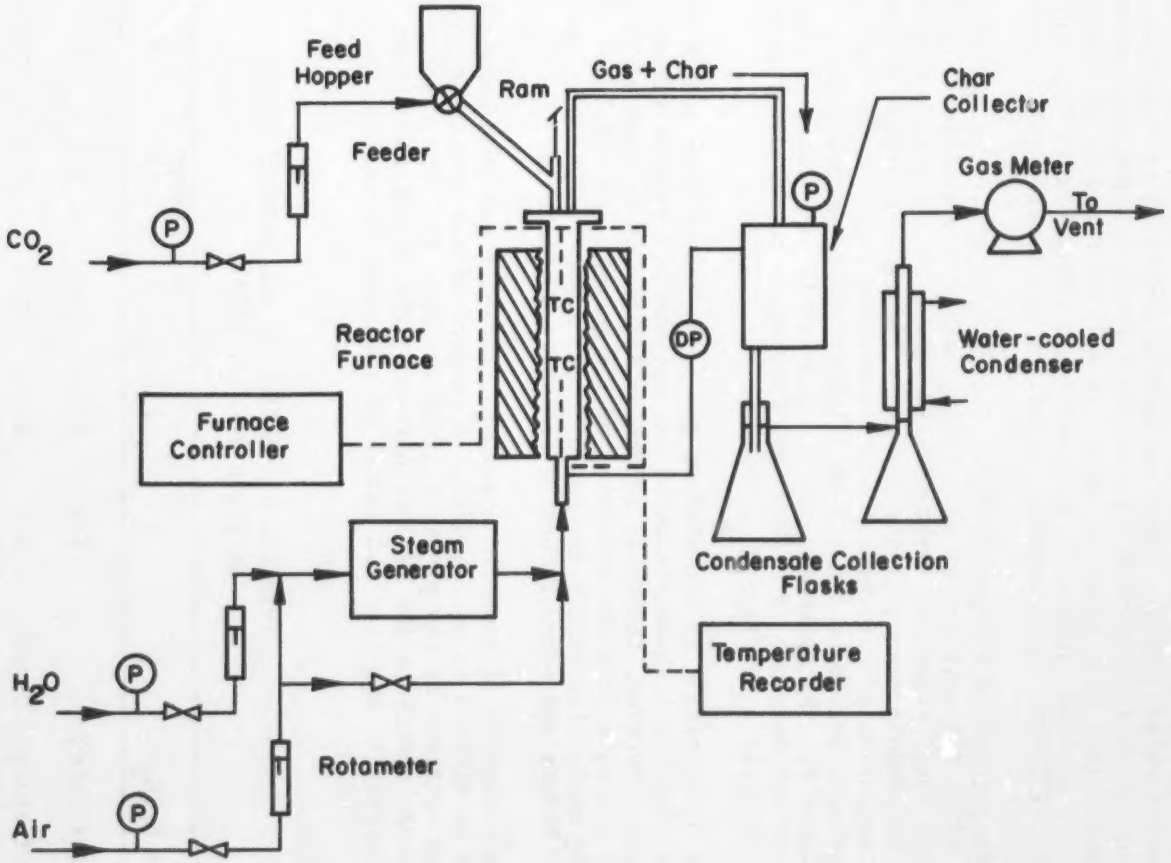


Figure 4. Partial oxidation of manure - flow diagram (Halligan et al., 1974)

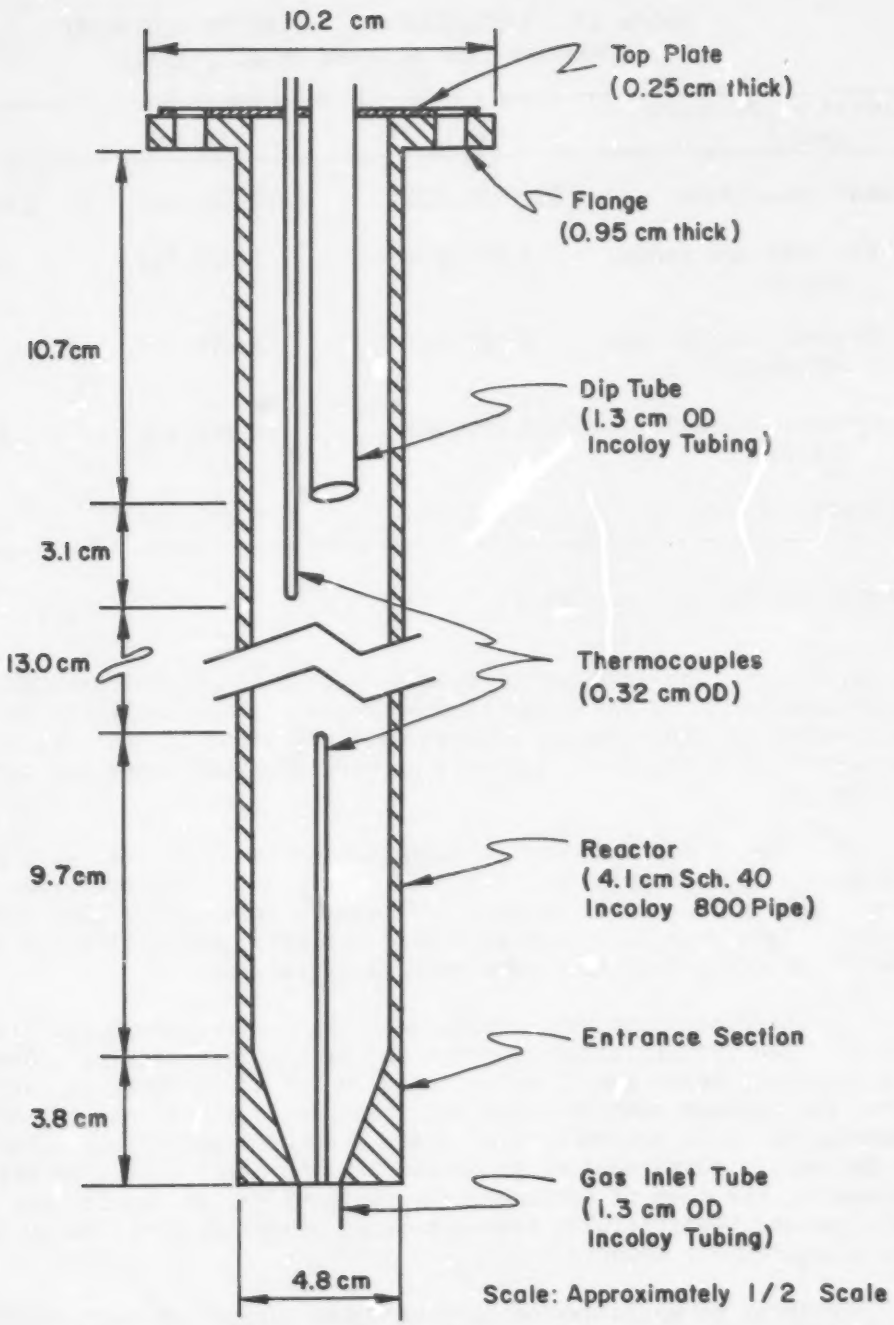


Figure 5. Reactor details (Halligan et al., 1974)

Table 17. INSTALLED COST OF MAJOR EQUIPMENT
(adapted from Wideman et al., 1974)

Operating Pressure (psig)	30	100	340
Total Investment	$31,887,110	$22,523,940	$14,150,240
Reactors and feeder section	4,942,500	5,405,740	6,013,850
Desulfurization and reforming*	8,832,730	5,811,178	3,636,610
Compressors and boilers	18,048,100	11,293,408	4,482,790
Operating Costs	4,446,120	3,286,190	2,592,580

*Does not include catalysts

firebricking. The lock hopper feeders and solids dischargers themselves comprise nearly 35% of the total reactor costs. There is little option in this section of the plant from a process design standpoint, but the investment can be decreased if the mass flux rate can be increased above the assumed 150 lb/ft^2-hr.

The most convenient way to summarize costs associated with processing the manure is to determine a value for the product gas for break even operation. This was done for several different assumed values for the cost of manure. This cost is primarily a transportation cost, although the manure itself may ultimately have some value as fertilizer.

The product value was determined using a discounted cash flow type calculation. The industrial environment and assumptions used are shown in Table 18. The resulting costs are shown in Table 19 for a 10% interest rate. As can be seen, the minimum cost for producing the gas is $10.47 per ton of equivalent ammonia, or 13.5¢ per MSCF of ultimate synthesis gas. This minimum cost occurs if the manure costs nothing to deliver to the plant site. As this manure cost increases, the cost of producing the gas goes up, as can be seen in Table 19. Halligan and Sweazy (1972) have estimated a synthesis gas value of $12.50 per ton of equivalent ammonia.

In terms of solid wastes disposal, the investment costs of the process is $4,625 per daily ton of manure processed, but in terms of production, the investment becomes $10,165 per daily equivalent ton of ammonia.

TABLE 18. ECONOMIC CRITERIA (adapted from Wideman et al., 1974)

Size, tons NH_3/day	1,000
Project life, years	20
Depreciation Schedule, year sum of digits	11
Interest rate, % year-end discount	10, 14
Income tax, %	48
Fixed capital investment (FCI), % of major equipment costs	4.1
Maintenance, % of FCI/year	4
Salvage, % of FCI	5
Supervision, % of labor	20
Labor, dollars/operating man hour	5
Payroll, % of labor + supervision	25
Plant overhead, % of labor	50
Working capital, % of FCI	5

Table 19. COST OF SYNTHESIS GAS PRODUCTION*
(adapted from Wideman et al., 1974)
(340 psig Operating Pressure)

Manure Cost** ($/ton)	$0.00	$1.50	$3.00
Synthesis gas cost per ton of equivalent ammonia ($/ton)	10.47	13.77	17.06
Cost per MSCF of synthesis gas ultimate ($/MSCF)	.135	.177	.220

* Includes 10% discounted cash flow on investment
**Delivered to plant site

The results of this basic evaluation of the process utilizing the small bench scale reactor were sufficient for the researchers to conclude, "The SGFM project has been shown to be technically, as well as economically, attractive for additional research. For this reason, and the probability of future curtailment of natural gas feedstock supplies, continued development of the process is advisable" (Wideman et al., 1974).

Walawender et al. (1973a) described the ammonia synthesis gas recovery process in detail with material and energy balance equations utilized in specifying the major items of equipment. Walawender et al. (1973b) also present an economic evaluation of the process. Their evaluation was based on a design capacity of 1,100 tons of wet manure per day. The gaseous product amounts to some eight million scf per day. No credit was assumed for the char by-products of the process.

The estimated capital investment for the synthesis gas process is presented in Table 20. Total product cost estimates for the synthesis gas process are presented in Table 21.

Table 20. ESTIMATED CAPITAL INVESTMENT FOR SNYTHESIS GAS PROCESS (Walawender et al., 1973b)

Item	Cost
A. Direct Costs	$
1. Purchased Equipment (delivered)	629,700
2. Equipment Installation	220,400
3. Instrumentation and Controls (installed)	63,000
4. Piping (installed)	157,400
5. Electrical (installed)	56,700
6. Buildings	125,900
7. Yard Improvements	50,400
8. Service Facilities (installed)	251,900
9. Land	37,800
TOTAL DIRECT PLANT COST	1,593,200
B. Indirect Costs	
1. Engineering and Supervision	207,800
2. Construction Expenses	188,900
3. Contractor's Fee	125,900
4. Contingency	220,400
FIXED CAPITAL INVESTMENT	2,336,200
C. Working Capital	350,400
TOTAL CAPITAL INVESTMENT	$2,686,600

Table 21. TOTAL PRODUCT COST ESTIMATED FOR SYNTHESIS GAS PROCESS (Walawender et al., 1973b)

Item	Cost
I. Manufacturing Cost	$
A. Direct Production Costs	
1. Raw Materials	
Manure	360,000
2. Operating Labor	118,300
3. Direct Supervisory and Clerical Labor	17,800
4. Utilities	121,300
5. Maintenance and Repairs	116,800
6. Operating Supplies	23,400
7. Laboratory Charges	11,800
B. Fixed Charges	
1. Depreciation	233,600
2. Local Taxes	23,400
3. Insurance	23,400
C. Plant Overhead Costs	59,200
II. General Expenses	
A. Administrative Costs	37,900
B. Distribution and Selling Costs	24,300
C. Research and Development Costs	36,400
D. Financing	5,400
ANNUAL TOTAL PRODUCT COST*	$1,212,900
TOTAL PRODUCT COST PER MSCF	$0.458

* Basis: 1,090 tons/day wet manure feed, 330-day/year plant operation.

Processing costs amount to $3.37 per ton of wet manure. Assuming that the gas product can be sold for $0.25/MSCF (the 1975 well-head price for natural gas has surpassed this amount), the processing is reduced to $1.53 per ton of wet manure. The breakeven sales price for the gas is $0.458/MSCF. The current breakeven price has increased by some undetermined factor due to recent widespread inflationary economic trends. Thus, present increases in well-head gas prices are offset by increased equipment, construction, and labor costs.

The above processing costs can be reduced through the utilization of the char to produce additional gas or used to reduce the quantity of purchased utilities. Optimization of the process should also contribute to cost reductions. Presently anhydrous ammonia is generated from methane. Natural gas reserves, the primary source of methane, have reached a critical level. In view of this, the economics can be expected to become very favorable in the near future.

Another process design to produce ammonia synthesis gas from manure was developed at Texas Tech University (Natour et al., 1975). A small scale air-fired cyclonic burner was constructed and operated to partially oxidize pulverized cattle manure without external heat or added fuel. The effect of increased reaction temperature, which varied from 1,110° F to 1,480° F, showed that if sufficient heat transfer between entering and exiting streams is achieved, and the product gas shifted and reformed, the projected ultimate hydrogen yield will range from 7.2 to 12.8 scf/pound of ash-free dry manure. Figure 6 is a flow diagram for the partial combustion of manure utilizing a cyclonic burner. Product analysis are presented in Table 6.

The results of the preliminary studies involving the bench scale fluidized bed reactor and the cyclonic burner to produce synthesis gas from cattle manure were used to design a "mini-pilot" plant at Texas Tech University, Figure 7 (Huffman, Halligan, and Peterson 1978). The plant, which is currently being evaluated, was designed to optimize the synthesis gas from manure production process. The reactor configuration was altered by placing an expanded pre-heating chamber at the top such that manure being fed into the reactor from the top would be pre-heated by heat radiated from the lower fluidized bed portion of the reactor. Thus, in concept heat that would be otherwise passed off with product gases would be utilized to lower the total energy requirements of the system.

The composition of the product gases as a result of this design configuration were unanticipated. The pre-heating chamber not only effectively raised the temperature of the incoming feedstock but at the same time provided a cooling chamber for the product gases which quenched the thermal transformation of the ethylene into methane. The resulting product gas, Table 6, characteristically contains commercially significant amounts of ethylene (Huffman, Halligan, and Peterson 1978).

The production of ethylene improves the economic feasibility of the process. Table 22 is a preliminary evaluation of the economics of the synthesis gas production process with consideration for the recovery of ethylene.

A combination of synthesis gas and ethylene production is the gasification process most likely to provide an attractive profit margin while reducing the animal wastes problem. Process economics could become even more attractive after additional optimization at the demonstration plant level. Many other solid wastes, such as cotton gin trash, grain cropping wastes, municipal refuse, peanut hulls, etc., are being evaluated in the "mini-pilot" model. Favorable data from these evaluations could result in the construction of plants near large metropolitan and farm centers. These locations would provide manure disposal access for animal production facilities which

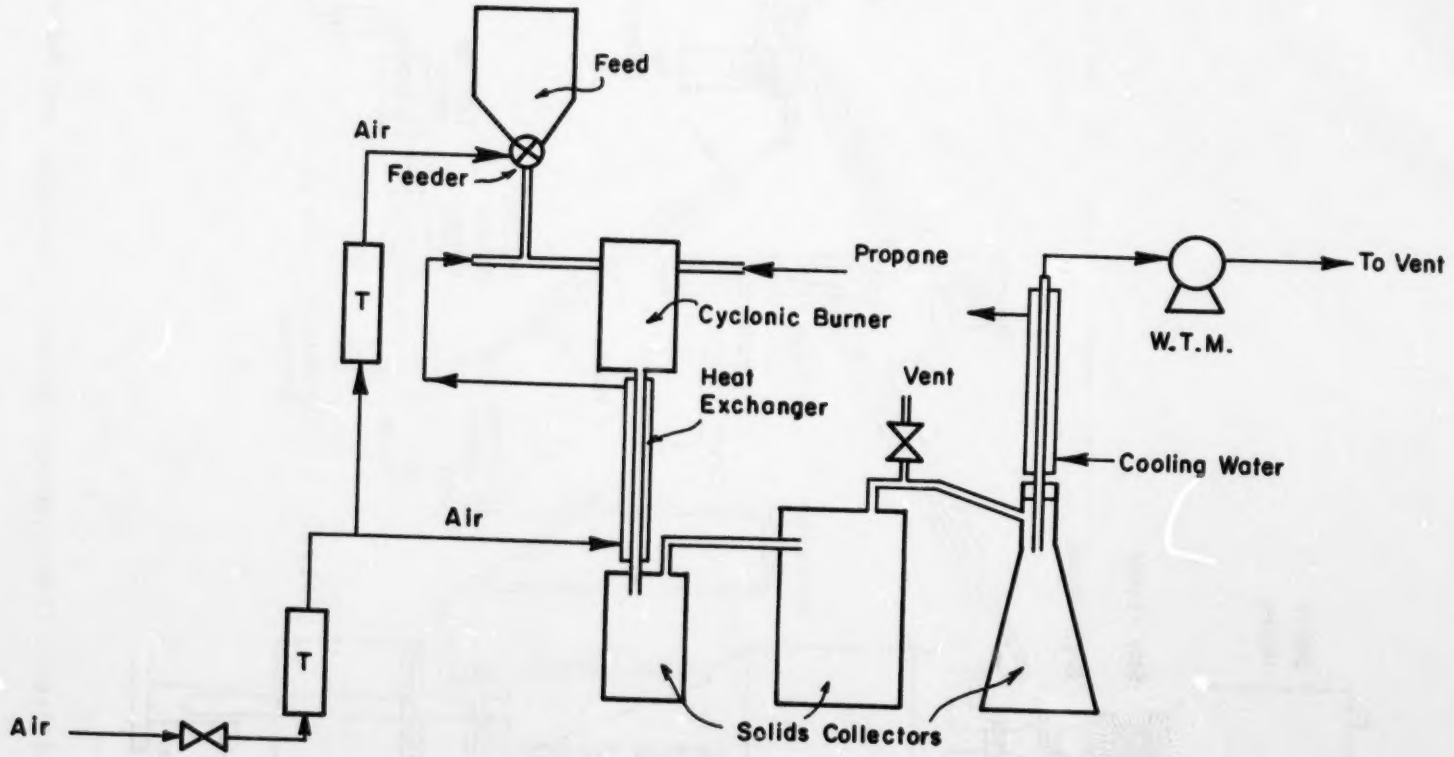


Figure 6. Flow diagram for the partial combustion of manure utilizing a cyclonic burner (adapted from Natour et al., 1975)

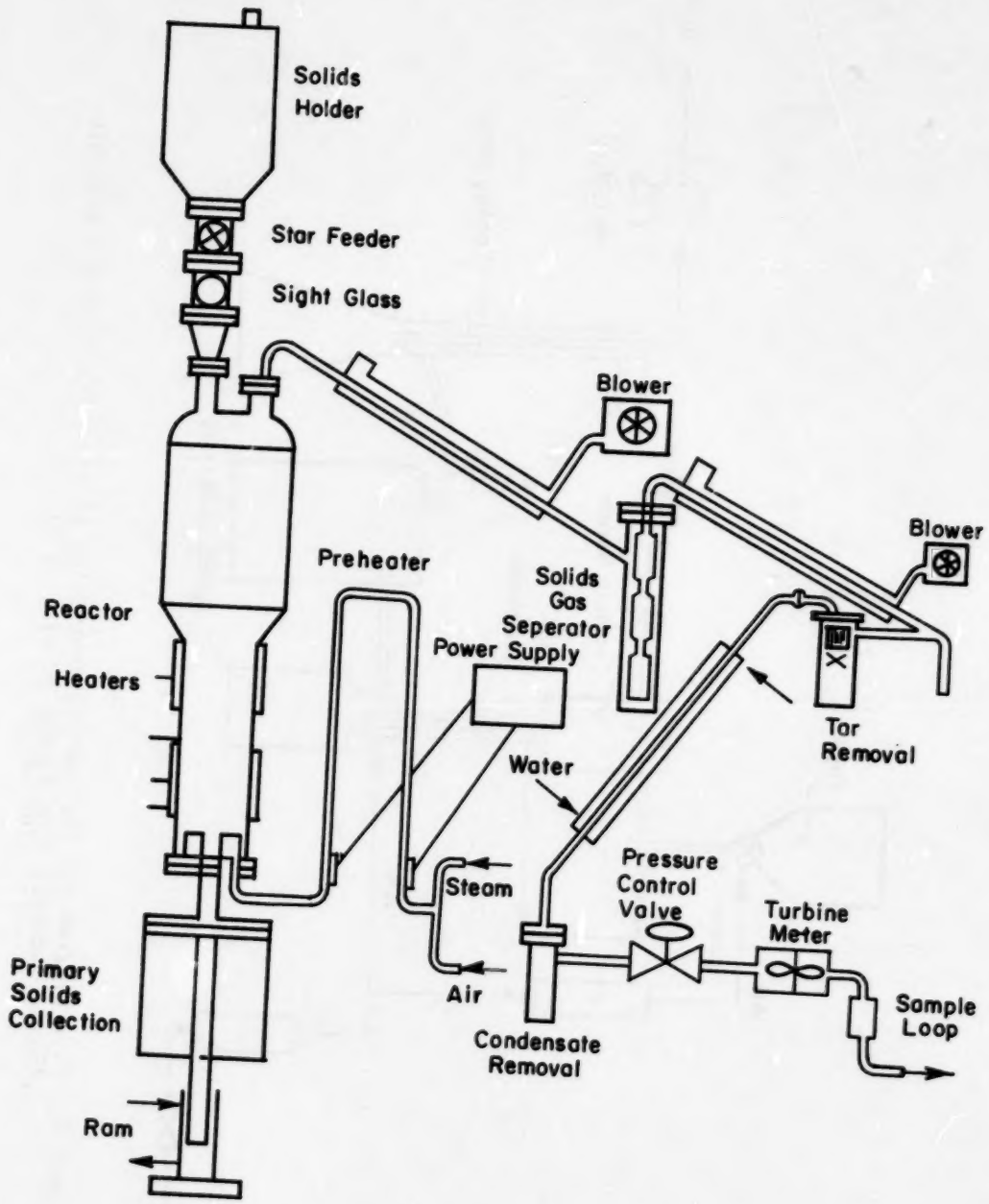


Figure 7. Syn-Gas-II flow schematic (Huffman, Halligan, and Peterson, 1978)

Table 22. PRELIMINARY ETHYLENE PRODUCTION FROM MANURE ECONOMICS (Huffman and Halligan)†

Item	Cost
I. Reactor and Feed Section Costs*	$ 6,000,000
II. Gas Recovery	22,000,000
A. Site Development	
B. Working Capital	
C. Engineering	
D. Buildings	
E. Fire Brick Design on Reactor	
F. Downtime Contingencies	
G. Process Water Treatment	
TOTAL INVESTMENT TO BUILD PLANT IN 75 DOLLARS	$28,000,000
III. Operating Costs**	
A. 10-year 10% interest	
B. Manure cost of 1.50/T	
C. Labor and Supervision	
D. Plant Overhead	
E. Taxes, Utilities	
TOTAL OPERATING COSTS	$ 7,000,000
Annual Value of Ethylene***	$ 2,750,000
Annual return on $28,000,000 investment, (%)***	9.47

† Personal Communication with W. J. Huffman and J. E. Halligan Texas Tech University.

* Reactor costs based on capacity of 150# manure/hr/ft^2.

** No char energy allowance or pollution control incentives.

*** Value of product and annual return on investment based on:

1. Number of cattle = 400,000 head one time capacity.
2. Tons of ash free manure = 1,200/day.
3. Total product gas yield = 48 scf/ton manure.
4. Pounds of ethylene per year = 74,100,000.
5. Pounds ethylene per pound of dry ash free manure = 0.094.
6. Ethylene yield is based on 20 scf of product gas/pound of dry ash free manure at 6% ethylene in product gas.
7. Value of ethylene = $0.12/lb.
8. Taxes = 50% of product value.

are much smaller than the large concentrations of animals now required to exceed the economic break points.

CHAR AND CARBON RECOVERY

The basic products of most pyrolysis processes are tars, gases, aqueous liquids, chars, and ash. The chars and ash are usually combined in the raw product form. The ratio of tars to ash is usually a function of the amount of soil mixed with the raw manure feedstock. Manures from soil or "dirt" lots usually are very high in soil and subsequently ash content due to the mixing actions of the trampling of manure and soil by the cattle or the grazing of the cattle at available manure soil interfaces. Concrete based lots may even have relatively high soil or ash content in manure generated by animals which are fed rations which are contaminated by wind blown dust at or before harvest.

Many researchers have suggested that the char could be used to supplement heat energy used to maintain pyrolysis. Others advocate the recycle of the char back through the process to recover additional tars or gaseous fractions. In both instances there is a certain percentage of residual ash containing a concentrated form of salt equal to that quantity which was in the original feedstock. Salt buildup in the wastes is one of the major problems of the original concept of land disposal of animal wastes. Salts are not changed or reduced in these reactions; therefore, there is a tendency to concentrate salts per unit of volume in the reduced total volume of final wastes which must ultimately be disposed. Thus, by necessity one will need approximately the same acreage to dispose of these chars as was needed to dispose of the original volume of manure. Landfills on dedicated sites are conceivable as the volume of the char is considerably less than the volume of manure throughout, so less land would be needed for this type of disposal. However, problems concerning groundwater contamination could arise as a result of landfilling chars in some geographical areas.

An alternative to land disposal and/or landfill of the char could be to consume it in the manufacture of some product. Characteristically product(s) should be so selected that a large amount of char could be used in their manufactures with some financial return on the investment.

Char called TCD (treated cow dung) has been evaluated for use as a lamp black substitue in ink, rubber, and paint; as a filler and carbon source in charcoal briquettes; as a filler in hot pressed ceramic tiles; and as a foaming agent in the fabrication of lightweight foamed glass (Mackenzie, 1976) (Anon., 1975). As a lamp black substitute, the char should be free of ash and corresponding grit. The chars tested were only marginally acceptable for ink filler and pigments; however, rubber samples made from char lamp black substitutes tested satisfactorily. Charcoal briquettes made from the char had burning characteristics comparable to compressed wood chip charcoal presently on the market.

Chars with higher ash content were satisfactory as fillers in paint and ceramic tile, while the most promising use investigated in this study was the manufacture of glass foam. This process utilizes two solid waste materials,

scrap glass and char. TCD milled to a minus two hundred mesh particle size is mixed with powdered scrap glass. This mixture is fired in a mold to a temperature at which the glass softens. At these temperatures, the carbon in the TCD carbonizes to CO_2 and creates small pores in the softened glass. These small pores are trapped upon cooling and a foam like cellular structure results. The light weight glass foam can be fabricated in a wide range of sizes, shapes, densities, and appearances. This material has excellent thermal, sound, and electrical insulative properties and is nonflammable, light, strong, chemically resistant and durable (Mackenzie, 1974; Mackenzie, 1975). Fabricated of TCD-scrap glass foam insulation materials are estimated to be competitive with commercially available foam glass products which are fabricated from new glass and specially prepared chemical foaming agents. Mackenzie (1976) also suggests that (1) tars condensed from the production of TCD potentially are useable as a crude oil source, (2) the aqueous liquids produced have a potential fertilizer value as they are very high in nitrogen, and (3) gases produced could be used to supplement process heat requirements. The characteristics of the char and other products of the UCLA process which are being evaluated by Mackenzie are presented in Table 6.

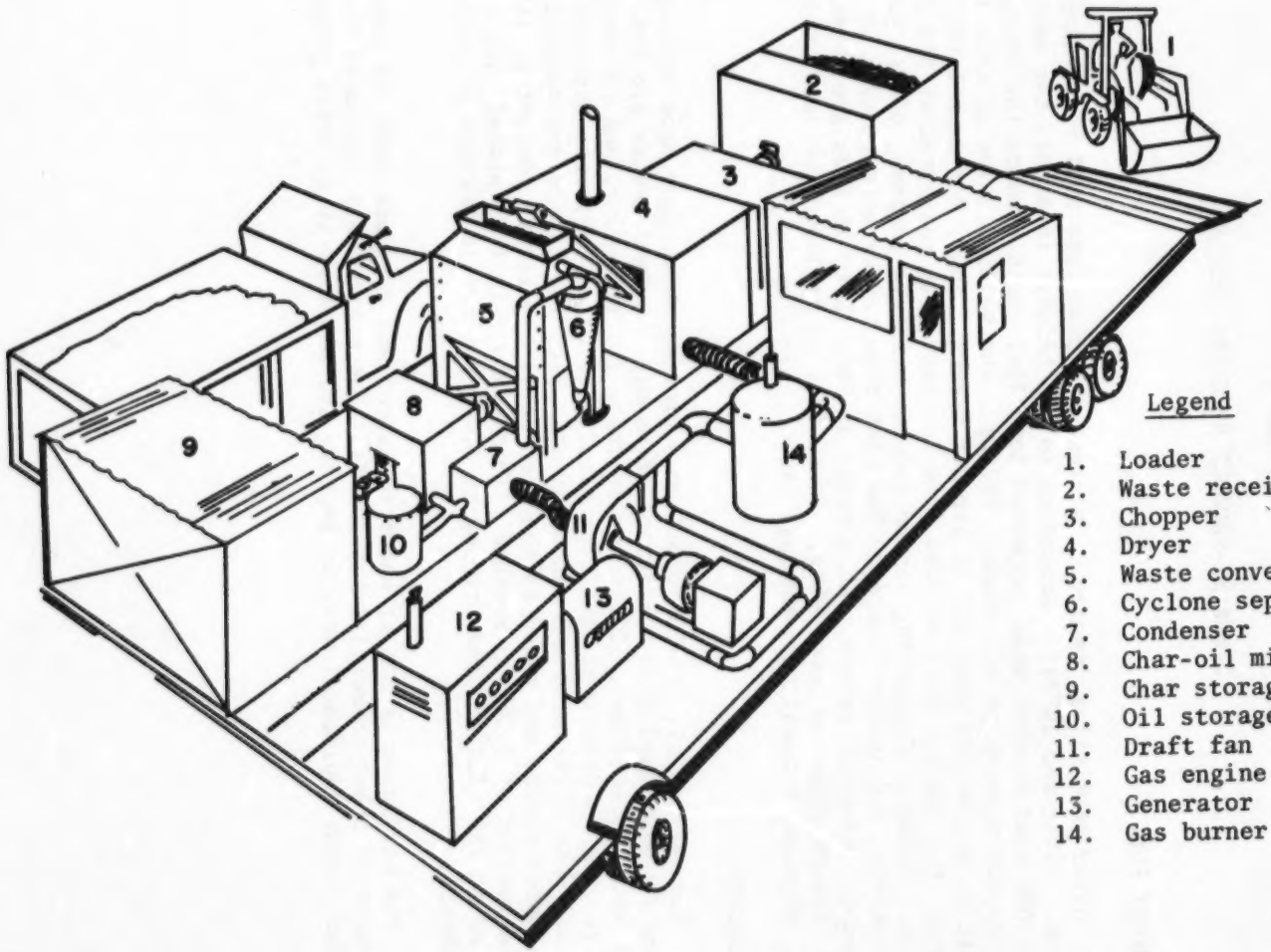
An evaluation of the chemical and physical properties and potential uses of chars produced by the Texas Tech synthesis gas process was presented by Kara et al. (1975). The potential uses which Kara evaluated were using char and ash as a primary fuel, a potassium fertilizer and a lime soil conditioner, an adsorption media to remove synthetic color from water, a coagulant aid, and an admixture in cement, concrete, or lime. The results of this characterization and evaluation showed that potassium, sodium, calcium, magnesium, phosphorus, silicon, chloride, and sulfate are the major constituents of the ash fraction. The specific gravity of this ash varied from 2.02 and 2.46 and the fusion temperatures ranged from 1,099° C to 1,288° C. The water soluble content varied from 32% to 51% with potassium, sodium, chloride, and sulfate being the major soluble constituents of the ash. There was little variability in the physical and chemical characteristics of the ash from two different feedlots. The char has a low heating value, is difficult to ignite, and produces a large quantity of refractory ash; thus, the prospects of using char as a primary fuel are not encouraging. However, its use as a supplemental fuel may be feasible.

Manure ash contains from 15.06% to 24.10% potassium, expressed as potash (K_2O), and from 6.02% to 6.82% calcium, expressed as lime (CaO), indicating a potential usefulness as a potassium fertilizer and a lime soil conditioner. However, the high sodium content may render such applications infeasible. The adsorption ability of char in removing synthetic color from water was close to that of activated carbon. Ash was also found to have appreciable color adsorbing capability.

The use of ash with aluminum sulfate in coagulation tests resulted in a slight turbidity decrease relative to aluminum sulfate alone. The reduction was not great enough, however, to warrant the use of ash as a coagulant aid. The composition of manure ash and its high percentage of soluble components indicate that its use as an admixture in cement, concrete, or lime may not be feasible. The groundwater pollution potentials of char and ash are not great; thus, they would seem quite conducive to disposal in a carefully designed landfill.

PORTABLE REACTORS

The discussion of thermochemical processes has been based on large fixed site reactors. Knight (1974) proposes an alternative to a fixed facility site. Figure 8 is an artists concept of Knights proposed portable pyrolysis unit. The truck mounted reactor would periodically make visits to feeders on an established route converting their manure wastes into the various products of pyrolysis for a minimal fee or payment depending upon the final economic analysis in a working situation.



Legend

1. Loader
2. Waste receiving bin
3. Chopper
4. Dryer
5. Waste converter
6. Cyclone separator
7. Condenser
8. Char-oil mixer
9. Char storage
10. Oil storage
11. Draft fan
12. Gas engine
13. Generator
14. Gas burner

Figure 8. Portable waste conversion pyrolysis unit (adapted from Knight et al., 1974)

SECTION 6

OTHER BY-PRODUCT RECOVERY SYSTEMS

COMPOST FUEL

After composting, manure is a clean, sulphur-free fuel resembling lignite (Anon., 1974d and 1974e). According to one midwest inventor, the wastes from a 60,000 head feedlot when composted into fuel could produce the energy value of 109,440 barrels of oil (Anon., 1974d). The selling value of this fuel would be $1,094,400 with oil at $10 per barrel. Thus, for each 1,000 head of cattle, the compost-fuel derived from lot wastes is estimated at $18,240 (Anon., 1974e). Composting manure reduces moisture content, odors, pollution potentials, and health hazards. The heat required by this process is produced by bacterial action. An average of from 15 to 28 BTUs are created for each BTU expended in processing. Thus, fuel is produced for lower costs than oil, propane, natural gas, or coal (Anon., 1974e).

HARDBOARD

Sloneker et al. (1972) report on a process which they have developed to produce a hardboard from a fraction of manure. Animal wastes are fractionated into (1) solubles, (2) solids suitable for refeeding, and (3) residue. The residue is dispersed with hypochlorite solution. Fibrous material is recovered by filtration and vacuum dried. Then the fibers are sprayed with an aqueous resin, and mixed in the open until a moisture content of 11% and a resin content of 6.36% is reached. This mixture is then placed into a mold, heated to 250°-350° C, and pressed to 1,000 psi for 10 minutes to produce a hardboard.

The hardboard is not as water resistent and does not have the board strength of other commercial hardboards. The researchers concluded that the product needs additional work to improve it, but that it is still promising.

SECTION 7

SUMMARY

Several byproduct-recovery-from-animal-wastes schemes have been investigated. None of the systems have been developed to a point where they could be reduced to practice on a commercial scale. Many of the processes, however, appear to be very promising and could, with additional optimization, provide substantial monetary returns on initial investments. Many processes are viable alternatives to the present land disposal of animal wastes and disposal/treatment processes now being used for other highly organic solid wastes.

One of the schemes which is receiving a lot of public attention in view of the present energy "crunch" is anaerobic fermentation to produce methane. This process, which is technically quite feasible, has been known for several years and never reduced to commercial practice. Highly organic nitrogen-rich livestock wastes must be diluted with water to prevent toxicity to the microbes which produce the gas. This dilution can double and triple the volume of wastes which must be handled after digestion. Other factors which are deterrents to the economic feasibility of the process are:

1. Financial returns from the gas and/or electricity generated are not ample to justify the capital equipment and construction costs.
2. Detention time of wastes in the generator ranges from 10-20 days. The longer detention times which accumulate greater amounts of manure not only increase methane production per unit of wastes but also increase reactor size and operation costs.
3. Anaerobic digestion is only a partial waste stabilization process. Therefore, additional stabilization must follow the methane production step or the greater diluted volume of wastes must be handled for disposal in the same manner as the original feedstock to the process.
4. Methane to air ratios of from 1:7 to 1:2 are highly explosive, thus, caution should be exercised in the design and placement of various components of a system.
5. Microorganism communities within digesters can be eliminated by contamination with toxic substances.
6. Methane must be compressed to at least 2,100 psi to have an equivalent power to volume ratio as gasoline. Thus holding tanks are very large and heavy. Automobiles, for example, are known to utilize 5 to 15 cubic feet per mile. The fuel tank with a capacity for the average traveling radius would weigh several hundred pounds.

Even with all of these disadvantages, the process could have some application for supplying a continuous power need or for introduction directly into a methane transport pipeline.

The production of pipeline gases and oil like hydrocarbons from the highly organic animal manures is by no means a proven process. Much work still remains to be done to develop and optimize an economically feasible conversion process. The state-of-the-art could have been significantly advanced in this area were it not for drastic funding cuts to programs within Federal agencies which were conducting this research (Anon., 1974f). These cutbacks are all in view of recent energy shortages with resulting need for Federally imposed energy legislation and the findings and recommendations of the President's Water Pollution Control Advisory Board (Anon., 1971-72), which states:

> "The board believes that recycling animal wastes back onto the land is the best practicable approach in most situations, particularly for small operations, through the use of catchment basins, lagooning systems, and/or solid waste handling techniques. There are also other possible uses which should be given full consideration. Testimony presented to the Board indicates that promising possibilities exist in converting animal wastes into fuels, such as oil or gas, building materials, dry fertilizer, tires, etc., and in recycling back into animal feeds.
>
> Recommendation: That the Environmental Protection Agency give high priority to funding for research and development projects which may develop practicable and safe alternate uses for animal wastes."

The U.S. Bureau of Mines (Anderson, 1972) reports an estimated two billion tons of U.S. annual production of organic wastes of which 880 million tons are moisture and ash free organic material which could be used to produce an approximated two barrels of oil per ton. The energy requirement to accomplish this would be equivalent to 0.75 barrel of oil, leaving a net production of 1.25 barrels per ton of dry organic material processed. Vaughn (1971) reports that about four-fifths of the total annual solid waste production in the U.S. is animal manure.

The thermochemical process which appears to be the most economically attractive is ethylene production by the Texas Tech process. The economic outlook for all of the thermochemical processes would appear to limit the use of such systems to locations where large amounts of manure and other organic wastes can be readily accumulated. Thus, location of conversion facilities near large metropolitan areas could help alleviate solid municipal and domestic waste problems while affording the smaller animal producer within an economically feasible hauling distance an opportunity to dispose of his manure wastes.

REFERENCES

Allred, E. R. 1966. Farm-waste management trends in northern Europe. Proc. Management of Farm Animal Wastes. Michigan State University, East Lansing Michigan. pp. 133-136.

Anderson, T. L. 1972. Energy potential from organic wastes: a review of quantities and sources. Information Circular 8549. USDI, Bureau of Mines. 16 pp.

Andre, P. D. 1973. A feedlot without waste. Beef 10 (1):55-66, 69-70.

Anon. October 1971 and January 1972. The relationship between animal wastes and water quality. Report of meetings, President's Water Pollution Control Advisory Board and Environmental Protection Agency. Washington D.C. 33 pp.

Anon. 1973. Texas chemists working on process to convert manure into a useable fuel. Beef. 10(4):37.

Anon. 1974a. Bioconversion. Second Edition, No. 40. Hearing before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, Ninty-third Congress. Washington D.C. 425 pp.

Anon. 1974b. Natural gas from the barnyard. Conservation News. 39(2):2-4.

Anon. 1974c. Convert output to input. Big Farmer. September 1 p.

Anon. 1974d. Manure as a fuel. Calf News. 12(3):48, 86-87.

Anon. 1974e. Composted manure called "available fuel source." Feedlot Management 16(4):28, 30.

Anon. 1974f. Control of pollution from animal feedlots and reuse of animal wastes. Fourteenth Report by the Committee on Government Operations, together with supplemental and dissenting views. U.S. Govt. Print. Off., Washington, D.C. 68 pp.

Anon. 1975. The shh...you-know-what-brick. New Scientist. July p. 564.

Appell, H. R., Y. C. Fu, S. Friedman, P. M. Yavorsky, and I. Wender. 1971. Converting organic wastes to oil. Report of Investigations 7560. U.S. Bureau of Mines, Pittsburgh Energy Research Center, Pittsburgh, Pa. 20 pp.

Appell, H. R. and R. D. Miller. 1972. Fuel for agricultural wastes. Symposium: Agricultural and Municipal Wastes, New York, N.Y. pp. 84-92.

Appell, H. R., I. Wender, and R. D. Miller. 1970. Conversion of urban refuse to oil. U.S. Department of the Interior, Washington D.C. 5 pp.

Barth, C. L. and D. T. Hill. 1975. Energy and Nutrient Conservation in Swine Waste Management. Paper No. 75-4040, Annual Meeting of American Society of Agricultural Engineers. University of California, Davis, California, June 22-25. 16 p.

Bohn, H. L. 1971. A clean new gas. Environment 13(10):4-9.

Costigane, W. D., D. H. Edwards, D. R. Fraipont, G. R. McClean, J. H. Pinchin, and B. H. Younger. 1972. Methane production from anaerobic digestion of animal wastes. University of Waterloo, Waterloo, Ontario. 75 pp.

Davis, E. G., I. L. Feld, and J. H. Brown. 1972. Combustion disposal of manure wastes and utilization of the residues. Technical Progress Report No. 46. USDI, Bureau of Mines. U.S. Department of the Interior, Washington D.C. 9 pp.

Day, D. L., E. L. Hansen, and S. Anderson. 1965. Gases and odors in confinement swine buildings. Transactions of ASAE 8(1):118-121.

Fairbank, W. C. 1974. Fuel from feces? Paper No. PC 74-03. ASAE Pacific Region Meeting, Phoenix, Arizona. pp. 20-23.

Feldmann, H. F., K. D. Kiang, C. Y. Wen, and P. M. Yavorsky. October 1973. Cattle manure pipeline gas. Mechanical Engineering. pp. 36-41.

Feldmann, H. F., C. Y. Wen, W. H. Simons, and P. M. Yavorsky. 1972. Supplemental pipeline gas from coal by the hydrane process. Presented at the 71st AIChE Meeting, Dallas, Texas. pp. 74-76.

Fosgate, O. T. and M. R. Babb. 1972. Biodegradation of animal waste by Lumbricus terrestris. Journal of Dairy Science 55(6):870-872.

Fry, J. T. 1973. Methane digestion for fuel gas and fertilizers. The New Alchemy Institute, Woods Hole, Mass. 9 pp.

Garner, W., C. E. Bricker, T. L. Ferguson, C. J. W. Wiegand, and A. D. McElroy. 1972. Pyrolysis as a method of disposal of cattle feedlot wastes. In: Waste Management Research. Proc. 1972 Cornell Agricultural Waste Management Conference, Cornell University, Ithaca, N.Y. pp. 101-123.

Garner, W., and I. C. Smith. 1973. The disposal of cattle feedlot wastes by pyrolysis. EPA-R2-73-096. U.S. Environmental Protection Agency. Ada, Oklahoma. 99 pp.

Goeppner, J. and D. E. Hasselmann. 1974. Digestion by-product may give answer to energy problem. Water and Wastes Engineering. 11(4):30-35.

Halligan, J. E., K. L. Herzog, H. W. Parker, and R. M. Sweazy. 1974. Conversion of cattle feedlot wastes to ammonia synthesis gas. EPA-660/ 2-74-090. U.S. Environmental Protection Agency. Ada, Oklahoma. 45 pp.

Halligan, J. E. and R. M. Sweazy. 1972. Thermochemical evaluation of animal waste conversion processes. Paper presented at the 72nd National Meeting of AIChE, St. Louis, Missouri. 21 pp.

Hancock, R. S. April 1956. His broilers thrive on worm compost. Farm Journal. p. 18.

Hansen, R. W. 1976. Methane Generation from Livestock Waste. Neb Guide G 76-268. University of Nebraska, Lincoln, Nebraska.

Herzog, K. L. 1973. Synthesis gas from manure. M.S. Thesis. Texas Tech University, Lubbock. 34 pp.

Herzog, K. L., H. W. Parker, and J. E. Halligan. 1973. Synthesis gas from manure. Presented at the 73rd National Meeting of the AIChE, Detroit, Michigan. 17 pp.

Huffman, W. J., J. E. Halligan, and R. L. Peterson. 1978. Conversion of cattle feedlot manure to ethylene and ammonia synthesis gas EPA-600/ 2-78-026 U.S. Environmental Protection Agency. Ada, Oklahoma. 63 pp.

Kara, B. H., R. M. Sweazy, J. E. Halligan, and R. H. Ramsey. 1975. Utilization and disposal of residue from the partial oxidation of cattle feedlot manure. Texas Tech University, Lubbock. 76 pp.

Kiang, K. D., H. F. Feldmann, and P. M. Yavorsky. 1973. Hydrogasification of cattle manure to pipeline gas. Presented at the 165th National Meeting of the American Chemical Society, Dallas, Texas. pp. 15-20.

Knight, J. A., J. W. Tatom, M. D. Bowen, A. R. Colcord, and L. W. Elston. 1974. Pyrolytic conversion of agricultural wastes to fuels. Annual Meeting ASAE, Stillwater, Oklahoma. 25 pp.

Loehr. R. C. 1974. Agricultural waste management. Academic Press, New York, N.Y. 576. pp.

Mackenzie, J. D. 1974. Method of Making Foamed Glass Products with Excretia and Glass Batch. U.S. Patent No. 3,811,851, Assignee: The Regents of the University of California. U.S. Patent Office, Washington, D. C., May 21.

Mackenzie, J. D. 1975. Method of Making Glass Products. U.S. Patent No. 3,900,303, Assignee: The Regents of the University of California. U.S. Patent Office, Washington, D. C., August 19.

Mackenzie, J. D. 1976. Conversion of cattle manure into useful products. EPA-600/2-76-238. U.S. Environmental Protection Agency. Ada, Oklahoma. 33 pp.

Massie, J.R., Jr., and H. W. Parker. 1973. Continuous solid waste retort feasibility study. 17th National Meeting of AIChE, New Orleans, Louisiana. Paper No. 43a. 31 pp.

Meenaghan, G. F., D. M. Wells, R. C. Albin, and W. Grub. 1970. Gas production from feedlot wastes. Paper No. 70-907. ASAE Winter Meeting, Chicago, Illinois. 15 pp.

Natour, I. J., H. W. Parker, and J. E. Halligan. 1975. Production of ammonia synthesis gas from manure in a cyclonic burner. Paper presented at 79th National Meeting of the AIChE, Houston, Texas. 20 pp.

Parker, H. W., C. J. Albus, Jr., and G. L. Smith. 1973. Costs for large scale continuous pyrolysis of solid wastes. Paper No. 43b-rv. 74th National Meeting of AIChE, New Orleans, Louisiana. 25 pp.

Parker, R., F. Humenik, R. Holmes, and M. Overcash. 1974. Methane production from swine waste with a mesophilic solar and thermophilic reactor. Paper No. 74-3033. 5 pp.

Pfeffer, J. T. 1973. Anaerobic processing of organic refuse. Proc. Bioconversion Energy Research Conference, University of Massachusetts, Amherst. pp. 31-39.

Savery, C. W. and D. C. Cruzan. 1972. Methane recovery from chicken manure digestion. Journal Water Pollution Control Federation 44(12):2348-2354.

Schlesinger, M. D., W. S. Sanner, and D. E. Wolfson. 1972. Energy from the pyrolysis of agricultural wastes. Symposium: Processing Agricultural and Municipal Wastes, New York, N.Y. pp. 93-100.

Schneider, T. R. 1972. Substitute natural gas from organic materials. ASME Winter Annual Meeting, New York, N.Y. 13 pp.

Shuyler, L. R. 1973. National animal feedlot wastes research program. U.S. Environmental Protection Agency. EPA-R2-73-157. Ada, Oklahoma. 33 pp.

Singh, R. B. 1973. Methane power. Mother's Reprint No. 102. Mother Earth News, Madison, Ohio. 4 pp.

Sloneker, J. H., R. W. Jones, H. L. Griffin, K. Eskins, B. L. Bucher, and G. E. Inglett. 1972. Processing animal wastes for feed and industrial products. Symposium on Processing Agricultural and Municipal Wastes. New York, N.Y. pp. 13-28.

Smith, R. J. 1973. The anaerobic digestion of livestock wastes and the prospects for methane production. Midwest Livestock Waste Management Iowa State University, Ames. November 27-28. 30 pp.

Solomon, J. 1972. The social redemption of pure garbage. Sciences 12(6):13-15.

Sweeten, J. M. 1974. Methane production from animal wastes. Animal Wastes Management News. Texas Agricultural Experiment Station, Texas A&M University, College Station. 21 pp.

Taiganides, E. P. 1974. Coprology: a pollution solution? Agricultural Engineering 55(4):21.

Vaughn, R. D. 1971. Solid waste management--anybody's problem. Environmental Science and Technology 5:293.

Wadleigh, C. H. 1968. Wastes in relation to agriculture and forestry. Misc. Public. 1065. U.S. Department of Agriculture. Washington D.C. 112 pp.

Walawender, W. P., L. T. Fan, C. R. Engler, and L. E. Erickson. 1973a. Feedlot manure and other agricultural wastes as future material and energy sources: II. Process description. Report No. 45. Institute for Systems Design and Optimization, Kansas State University, Manhattan, Kansas. 31 pp.

Walawender, W. P., L. T. Fan, C. R. Engler, and L. E. Erickson. 1973b. Feedlot manure and other agricultural wastes as future material and energy sources: III. Economic evaluations. Contribution No. 33. Department of Chemical Engineering, Kansas Agricultural Experiment Station, Manhattan, Kansas. 23 pp.

Wells, D. M., G. A. Whetstone, and R. M. Sweazy. 1973. Manure, how it works. Presented at the ANCA-EPA Action Conference, Denver, Colorado. 18 pp.

Whetstone, G. A. 1973. Evaluation of proposed animal handling practices. Paper presented at the Rural Environmental Engineering Conference, Warren, Vermont. 5 pp.

Whetstone, G. A., H. W. Parker, and D. M. Wells, 1974. Study of current and proposed practices in animal waste management. EPA-430/9-74-003. U.S. Environmental Protection Agency. Ada, Oklahoma. 84 pp.

White, R. K. and E. P. Taiganides. 1971. Pyrolysis of livestock wastes. Proceedings International Symposium Livestock Wastes. The Ohio State University. Columbus, Ohio. pp. 190-191.

Wideman, W. S., J. E. Halligan, and H. W. Parker. 1974. Preliminary flow sheet and economics for production of ammonia synthesis gas from manure. Presented at 76th National Meeting of American Institute of Chemical Engineers, Tulsa, Oklahoma. 20 pp.

Wolf, M. 1974. Utilization of solar energy by bioconversion. Report No. 40. Bioconversion Science and Astronautics Committee of the House of Representatives. Ninety-third Congress. Washington, D.C. pp. 1-33.